Master Thesis

The rebound effect of energy-efficiency improvements

System dynamics modelling on rebound effects from improved automobile fuel-efficiency, integrating economic theory and social practice theory

by

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Abstract

Energy efficiency policies are being implemented by several states to reduce energy consumption and CO_2 emissions. The endeavours to increase energy efficiency assume that the improvement in energy efficiency will lead to a decrease in energy consumption and CO_2 emission. This assumption, however, might not become a reality if there appear significant behavioural responses in economy and society to the increased energy efficiency, known as 'rebound effects' (Herring and Sorrell, 2009).

Rebound effects are defined as the gap between expected reductions and actual savings in energy consumption due to improved energy efficiency through technological progress (Berkhout, Muskens, & Velthuijsen, 2000: 426; Binswanger, 2001: 120). The magnitude of rebound effects is critical to ensure the effectiveness of efficiency policies. If the rebound effects are greater than 100%, it is denoted as a 'backfire' effect, a paradoxical outcome triggered by the efficiency improvement, implying that energy consumption has increased due to the improvements in energy efficiency.

This study aims to investigate the causal mechanisms of generating rebound effects from improved energy efficiency by adopting a methodological approach based on system dynamics modelling. Different disciplines attempt to understand the essence of rebound effects and have explained the rebound generating mechanisms based on their ontologies (Polimeni et al., 2008; Wallenborn, 2018). System dynamics models are utilized as a practical research strategy to converge different disciplines and theories on rebound effects.

The system dynamics modelling on rebound effects in this study centres on the sector of automobile fuel efficiency in the EU countries. The modelling to analyse the rebound mechanisms from the improved automobile fuel efficiency is based on the integration of two disciplinary perspectives: economic theory and social practice theory. Computer simulations allow seeing the long-term effect of the enhancement in energy efficiency, compared to the baseline trend, showing the size of the contribution to the energy-saving goals.

The model does not concentrate on the estimation of the specific magnitude of the rebound effect. Rather, it aims to enlighten future trends in energy consumption and the possibility that backfires occur. Simulations and model structures have been meticulously inspected to understand the generating mechanisms of rebound effects. Furthermore, policy experiments are conducted to explore the policy options for rebound mitigation. Finally, the study discusses the simulation results to get meaningful policy insights and implications in terms of the effectiveness of efficiency policies on energy security and climate change.

The simulations and model structures gave insight into the relationships between fuel-efficiency improvements and energy consumption. The increase of fuel efficiency enables to drive more distances per unit amount of fuel, which creates more utilities and human welfare. However, it does not ensure a reduction in energy consumption. It is likely that it causes significant rebound effects leading to less than the expected reduction of energy consumption, or even backfires leading to an increase in energy consumption. Policy experiments elucidate possible pathways to decouple between energy consumption and driving distance as well as to overcome backfires.

Keywords: backfire, Jevons paradox, take-back effect, energy sufficiency, ecological modernisation

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Chapter 1. Introduction

1.1 Research background

As the urgency to tackle climate change and to secure energy resources increases, energy efficiency policies are being implemented by several states to reduce energy consumption and CO_2 emissions. Some European countries constitute a leading group regarding these policies. The European Union (EU) aims to increase energy efficiency at least up to 32.5% by 2030[1] compared to the baseline projection, by promoting technology development and innovation at all stages of the energy chain from the production to final consumption. The Energy Efficiency Directive (2012/27/EU) formulates schemes to help the member states to use energy more efficiently. In reaction to these aims, European countries have invested in more energy-efficient buildings, products, and organisation of transport (Fawcett, Rosenow, & Bertoldi, 2019).

All these endeavours to increase energy efficiency are based on the assumption that the improvement in energy efficiency will lead to a decrease in energy consumption and CO_2 emission. The following statements in the document published by the European Parliament clearly illustrate this underlying thought.

> *"By using energy more efficiently, energy demand can be reduced, leading to lower energy bills for consumers, lower emissions of greenhouse gases and other pollutants, reduced need for energy infrastructure, and increased energy security through a reduction of imports. Worldwide, energy efficiency has contributed to substantial savings in energy consumption (European Parliament, 2015: 1)"*

This assumption, however, might not (fully) become a reality if there appear significant behavioural responses in economy and society to the increased energy efficiency, known as 'rebound effects' (Herring and Sorrell, 2009). The rebound effects have been investigated by many scholars and there exists not much-disputed evidence that the rebound effects exist (Chakravarty, Dasgupta, & Roy, 2013; Vivanco, Kemp, & Van der Voet, 2016).

Rebound effects indicate the gap between expected reductions and actual savings in energy consumption due to improved energy efficiency through technological progress (Berkhout, Muskens, & Velthuijsen, 2000: 426; Binswanger, 2001: 120). The gap is derived from not expected and/or not anticipated, direct and indirect, behavioural and socio-structural changes which can offset the expected energy gains induced by improvements in energy efficiency. If the magnitude of rebound

[1] The target was revised upwards in 2018. The original target was at least 27%. The EU included the revised target in the 2030 Climate and Energy framework.

effects is significantly large, the effectiveness of the policies for efficiency improvements decreases because actual reductions in energy consumption would be relatively small, comparing to the targeted reduction level (Michaels, 2012; Chakravarty, Dasgupta, & Roy, 2013; Gillingham, Rapson, & Wagner, 2016).

There is an ongoing social debate among scholars as well as environmental activists, and policymakers, about which rebound effects will appear in the future and how small or large these rebound effects will be (Sorrell, 2007; Michaels, 2012; Chakravarty, Dasgupta, & Roy, 2013; Vivanco, Kemp,& Van der Voet, 2016). Previous studies estimating the economy-wide rebound effect have reported estimates with a variation from 15% to 350% (Dimitropoulos, 2007). It has become clear from these studies that the mechanisms underlying the emerging rebound effects are dynamic processes with complex interactions in the economy and society. These dynamics make it hard to trace the causal relationships creating rebound effects. The difficulties of the analysis and estimation of rebound effects prevent building a consensus on the issues of how serious the rebound effects have to be taken and how the large scale of rebound effects could be avoided (Van der Bergh, 2011; Irrek, 2011).

If the rebound effects are greater than 100%, it is denoted as a 'backfire' effect, a paradoxical outcome triggered by the efficiency improvement, implying that energy consumption has increased due to the improvements in energy efficiency (Jenkins, Nordhaus, & Shellenberger, 2011). The existing possibility of occurring backfires weakens the general confidence on the effectiveness of the energy efficiency policies regarding energy security as well as climate change mitigation. Since large uncertainties remain about the occurrence scale of rebound effects and their generating mechanisms, further research is needed on the socioeconomic mechanisms that create rebound effects and possible futures on energy efficiency policies given the existence of rebound effects, based on plausible theoretical explanations and relevant methodologies that adequately reflect the dynamics and complexity involved in the rebound processes.

1.2 Research aim and objectives

Most previous research investigating the rebound effects have relied on economic theories and econometric models (Berkhout et al., 2000; Dimitropoulos, 2007; Madlener & Turner, 2016). Theoretical explanations on rebound effects are based on the assumption of economic actors' behaviour and market mechanisms. In line with this, methodologies to estimate the magnitudes of rebound effects are dominated by a form of econometric modelling (Maxwell et al., 2011).

In recent years, not only economics but also other disciplines such as psychological, sociological, and industrial ecology have started to seek explaining why the rebound effect appears and why people change their behaviours after adopting efficient energy technologies and products (Peters & Dutschke, 2016; Santarius, 2016b; Labanca & Bertoldi, 2018). Different theories enrich and deepen our understanding of the rebound phenomenon, which broadens our view towards more complex and dynamic socio-economic mechanisms. Although through the participation of different academic fields, the theoretical explanation on rebound effects has become richer, the development of a relevant analytical methodology to encompass these different theories and perspectives is still in its infancy (Santarius, Walnum, & Aall, 2016).

This study aims to investigate the causal mechanisms of generating rebound effects from improved energy efficiency by adopting a methodological approach based on system dynamics modelling. The system dynamics models are expected to enable capturing the overall outcome from the complex socio-economic mechanisms producing rebound effects. The system dynamics models in this study will be developed based on an integrated view combining different branches of disciplines to explain rebound phenomena, mainly economic theory and social practice theory. To increase specificity, the models will be formulated focusing on the case of efficiency improvements in the automotive fuel sector. Although the models deal with this specific case of energy sectors, and conclusions will primarily focus on this case, an attempt will be made to also interpret and discuss the findings in the context of the broader debate whether improvements in energy efficiency are an effective solution to reduce energy use and to tackle climate change.

System dynamics models can be utilized as a practical research strategy to converge different disciplines and theories on rebound effects. Different disciplines attempt to understand the essence of rebound effects and explain the rebound generating mechanisms based on their own ontologies (Polimeni et al., 2008; Wallenborn, 2018). Gaps between different perspectives from the disciplines may inhibit further theoretical development on rebound effects and it often hampers constructive social debate on the effectiveness of energy efficiency policies (Santarius, Walnum, & Aall, 2016; Wallenborn, 2018). System dynamics allows implementing different mental models as one model. By adopting the system dynamics approach as an analytic methodology, it is expected to overcome the bounded ontologies of each discipline and to expand the theoretical explanations on the rebound effect by reflecting on multiple ontologies simultaneously.

This study will conduct system dynamics modelling to analyse the rebound mechanisms from the improved automobile fuel efficiency based on the integration of two disciplinary perspectives: economic theory and social practice theory. By simulations, the study explores the long-term effects of the rebounds on fuel consumption trends under different assumptions and scenarios.

Finally, the study will discuss the simulation results to get meaningful policy insights and implications in terms of the effectiveness of efficiency policies on energy security and climate change.

1.3 Research questions

This study seeks to answer the following three questions.

- What are the socio-economic mechanisms generating rebound effects?
- What would be the long-term developments in energy consumption under the rebound effect mechanisms?
- What are possible policy options to mitigate rebound effects?

To answer these questions, different theories on rebound effects are reviewed and the system dynamics model is formulated to assess the possible futures under the rebound effects. The model formulation and analysis are implemented within the case of the automobile fuel efficiency improvements.

1.4 Structure of the thesis

This study is composed of six chapters.

Chapter 1 introduces the research topic, including research background, research aim and objectives, and research questions.

Chapter 2 reviews the theoretical background of this study. The concepts of rebound effect and energy efficiency improvement are defined and previous studies and theories on rebound effects will be reviewed, focusing on economic theory and social practice theory.

Chapter 3 presents the research methodology. System dynamic modelling and its processes will be introduced. Also, the sector of automobile fuel efficiency for the model building is introduced.

Chapter 4 contains the contents of model formulation. Reference mode and model boundary are specified. Details of model building processes including dynamic hypothesis and parameter estimation will be reported. The model structures will be developed based on the theoretical explanation on rebound effects.

Chapter 5 reports the model results. It contains model testing and analyses with the model. The results of extreme condition test, behaviour reproducing test, and sensitivity analysis of model behaviours will be presented. Also, after the model testing, computer simulations will be performed to examine the long-term outcome of the increased energy efficiency. Simulations and model structures will be meticulously inspected to understand the generating mechanisms of rebound effects. Furthermore, policy experiments are conducted to explore the policy options for rebound mitigation.

Chapter 6 summarises the main findings and insight of the study. Also, the limitations of the study and suggestions for future research will be addressed.

Chapter 2. Theoretical Background

2.1 Defining energy efficiency

According to the EU Energy Efficiency Directive (2012/27/EU), energy efficiency is defined as “the ratio of the output of performance, service, goods or energy, to the input of energy”. The input of energy in this definition refers to “all forms of energy products, combustible fuels, heat, renewable energy, electricity, or any other form of energy”, whereas energy efficiency improvement means “an increase in energy efficiency as a result of technological, behavioural and/or economic changes”. Furthermore, energy savings indicate “an amount of saved energy determined by measuring and/or estimating consumption before and after implementation of an energy efficiency improvement measure, whilst ensuring normalisation for external conditions that affect energy consumption”. These definitions can generally be accepted to understand the meaning of energy efficiency but more specific definitions are required for measuring the energy efficiency as well as to discuss its improvement.

The system for converting input energy into useful outputs may be a device, a building, a firm, an industrial sector or an entire economy. For measuring the energy efficiency, therefore, it is necessary to define how to measure the input energy and the beneficial outputs, performances or products, produced in processes consuming energy. The output ‘products produced by consuming energy’ can refer to a large variety of objects, such as thermal comfort in buildings, transportation of individuals, a range of manufactured products (European Parliament, 2015). For example, when it comes to the heating system in buildings, the energy efficiency can be quantified as the temperature of a room per unit fuel or electricity consumption. On the other hand, the energy efficiency of vehicles can be measured as the driving distance per unit amount of fuel usage.

Basically, there are three options to measure the outputs in energy conversion systems (Sorrell, 2009: 1459). The first option is ‘thermodynamic measure’, such as heat content or the capacity to conduct useful work. The second option is ‘physical measure’, for instance, vehicle kilometres or tonnes of coals. The third option is ‘economic measure’, in which the outputs are defined such as Gross Domestic Product (GDP) or value-added monetary terms. When the term ‘energy efficiency’ is used, it is more common to measure the outputs using thermodynamic or physical measures. On the other hand, if the output is measured in monetary units, it is more common to call it ‘energy productivity’, rather than ‘energy efficiency (Berkhout, Muskens, & Velthuijsen, 2000; Sorrell, 2009).

Although energy efficiency should be measured in thermodynamic or physical measures, rather than in economic terms (Berkhout, Muskens, & Velthuijsen, 2000), GDP is often utilized as an indicator to measure the outputs of economy-wide energy efficiency. This ‘energy productivity of an economy’, calculated as the unit of GDP per unit of energy, is often used as a term referring to the energy efficiency of an economy or a nation. Also, as a similar concept and the converse measure, ‘energy intensity’ is widely used, which is defined as the unit of energy per unit of GDP.

Efficient energy use may result in the case of performing more tasks with the same amount of energy, which will lead to increased productivity. At the same time, it may produce the other case of achieving the same level of tasks with fewer energy inputs, which can contribute to energy conservation, as long as the conserved energy will not be used through rebound behaviours. This implies the fact that improvements in energy efficiency cannot guarantee anything about the absolute level of energy consumption in the future. The energy efficiency, by its definition, can only indicate a ratio of outputs to the inputs (Wallenborn, 2018: 2).

2.2 What is the rebound effect?

Rebound effects are described as follows: when the technology progress increases the efficiency of energy, the consumption of that energy also rises and eventually the expected savings in energy consumption from the increased efficiency is offset (Berkhout, Muskens, & Velthuijsen, 2000: 426; Binswanger, 2001: 120). They refer to the unintended outcomes of improvement in energy efficiency. Due to the rebound effects, energy consumption may not decrease as much as the amount intended by the energy efficiency improvement. In fact, energy consumption may even be higher than before. Rebound effects exist due to the appearance of social and behavioural responses to the measures to increase energy efficiency and they cause the energy savings to be less than the anticipated (Ehrhardt-Martinez & Laitner, 2010).

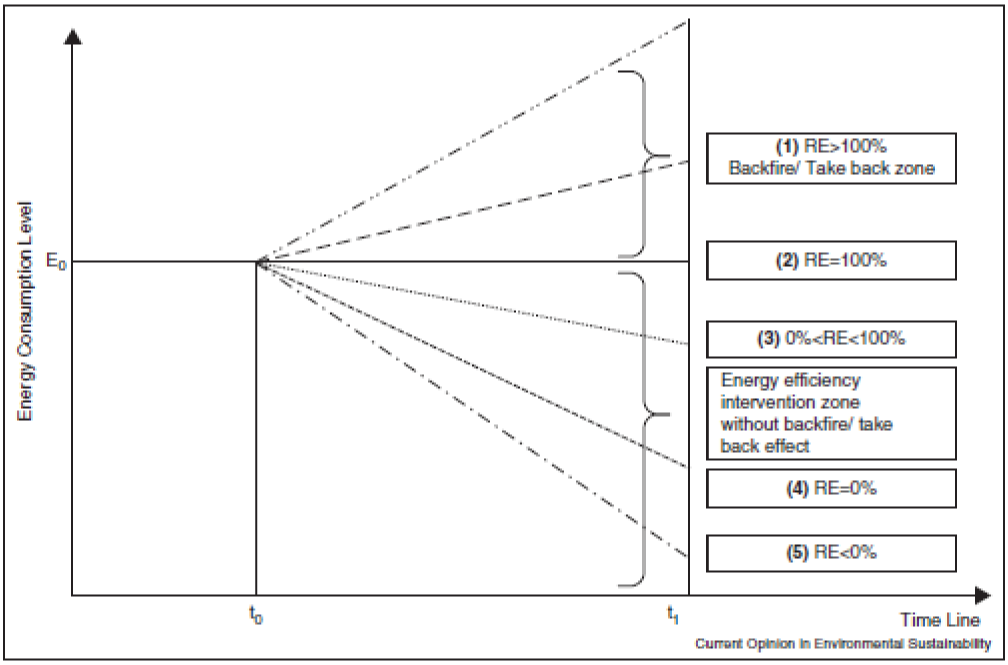
Rebound effects are typically denoted by the percentage of lost energy savings potentials derived from rebound behaviours. It is calculated as the ratio of the lost energy savings (‘expected savings - actual savings’) to the total savings expected from the energy efficiency improvement, indicated by the following formula.

$$\text{Rebound Effect} = (\text{Expected savings} - \text{Actual savings}) / \text{Expected savings}$$

For example, a 15% improvement of energy efficiency would technically allow for 15% reduction in energy consumption. However, the actual energy consumption reduction may be only

10%. In this case, the rebound effect would be 33.3% (calculated as (15-10)/15 = ⅓) (Haas and Biermayr, 2000). In other words, the 33.3% rebound effect means that only 66.7% out of the total expected energy reductions, technically estimated under the condition of implementing 15% efficiency improvement, are achieved, while 33.3% of them are eroded by the rebound effects.

Referring to differences in the magnitude of rebound effects from the increased energy efficiency, it is possible to project different future developments in the level of energy consumption (see Figure 2-1). If the magnitude of rebound effect ranges from 0% to 100%, it means there would be 'partial rebounds' and this would show the situation that energy is saved from the efficiency improvement, although (much) less than the expected energy savings (Chakravarty, Dasgupta, & Roy, 2013)



Source: Chakravarty, Dasgupta, & Roy (2013). p218.

Figure 2-1 Magnitude of rebound effect and change in the level of energy consumption

Theoretically, rebound effects could be zero or be smaller than 0%. If the rebound effect is equal to 0%, there are no rebounds and all the expected energy savings would be achieved without any erosion. Also, if the rebound effect is smaller than 0%, it indicates negative rebounds and there would be additional reductions in energy consumption more than the expected savings. This could be possible in case of an energy efficiency awareness campaign to induce behavioural change, which is very successful and generates larger savings than expected (Chakravarty, Dasgupta, & Roy, 2013)

When the magnitude of rebound equals to 100%, it is called ‘full rebounds’ and there are no energy reductions from the improved energy efficiency. The effect of efficiency improvement is exactly offset by the rebound effect. In case the size of rebound effects is larger than 100%, a so called ‘backfire’ situation occurs, which means that actual energy savings are negative: all expected energy savings are wiped out by the rebound effect. Furthermore, it illustrates a paradoxical situation that energy consumption appears to increase due to energy efficiency improvement. The backfire is also known as ‘Jevons paradox’ and ‘Take-back effect’ (Jenkins, Nordhaus, & Shellenberger, 2011; Chakravarty, Dasgupta, & Roy, 2013).

The magnitude of rebound effects is critical to ensure the effectiveness of efficiency policies. Only if the rebound effect is smaller than 100%, the policy measures for increasing energy efficiency would have energy savings, compared to the case in which the measures are not executed. There is little doubt about the existence of rebound effects but there are still debates about the magnitude of them.

2.3 Why does the rebound effect occur?

There have been theories on why rebound effects occur and what mechanisms works for it. Energy economics is the most leading group in this debate (Santarius, Walnum, & Aall, 2016). Scholars from this discipline explain why behavioural responses arise after an increase in energy efficiency based on rational individual decision making and the dominant role of price mechanism in the market. On the other hand, social practice theory, a relatively new theory in this research field, takes a different view on this topic. It explains that rebound effects occur because of changes in routinized activities of everyday life (Sonnberger & Gross, 2018). In the following subsections, these two approaches to rebound effects will be reviewed in more detail and the possibility of integrating the two perspectives will be examined.

2.3.1 Economic theory

1. Basic assumption

Economic theories on rebound effects follow the neoclassical economics point of view, which assumes that individual behaviours determine the overall economic system. Therefore, this theory starts the investigations on the rebound generating mechanisms at the level of individuals, such as consumers, firms, or households, and then expands the scope of the effects to macro-level. The theory assumes that individuals make their decisions in a rational way to increase their own utility and profits.

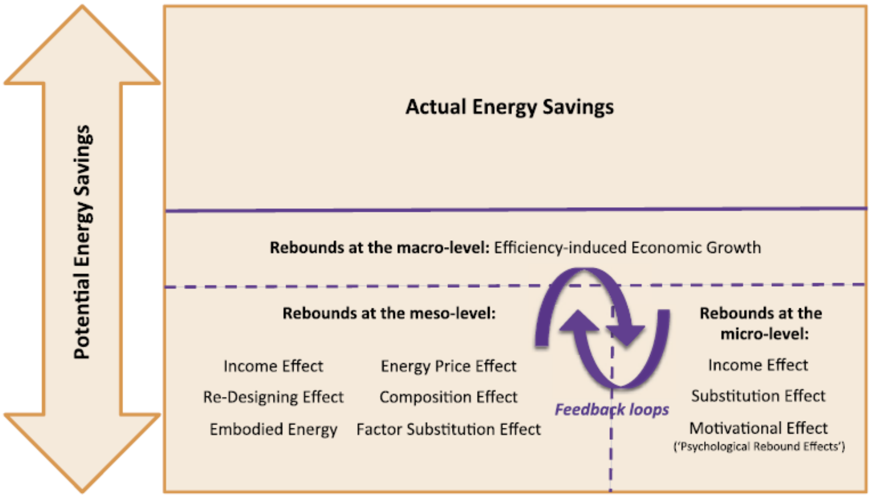
Research from this perspective on the rebound effects has focused on the cost savings and increased budget availability due to the efficiency improvements (Madlener and Turner, 2016; Wallenborn, 2018).

In the economic theory, since the whole economy is considered as a system composed of individuals and their choices, rebound effects are often distinguished into several types according to the aggregation level of individual's decisions, such as Micro-level, Sectoral or Meso-level, and Economy-wide or Macro-level (Sorrel, 2007; Madlener and Turner, 2016). Among them, micro-level becomes a starting point for the explanation on generating mechanisms of rebound effects. Further steps of the explanation of rebound effects on meso-level and macro-level rely on the interactions among individuals and the influence between different levels and sectors.

2. Rebound generating mechanism

Economic theories have explained the rebound effects as a collective outcome of individual choices in the market. Rebound effects can occur when an efficiency improvement lowers the price of an energy service by reducing the amount of energy input to provide the same level of service. It allows cost savings, which is the key issue in the explanation of rebound mechanisms. Individuals may respond to the change in price by changing their behaviours to increase their profits (Santarius, Walnum, & Aall, 2016).

The research on rebound effects in economics has used several denotations referring to such underlying mechanisms generating rebound effects in micro-level, meso-level, and macro-level. For example, income effect, substitution effect, embodied energy effect, re-designing effect, and energy price effect, which are presented in Figure 2-2. The mechanisms at micro-level and at meso-level might influence each other and they might form feedback loops creating dynamics (Santarius, 2016a).



Source: Santarius (2016a). p 410.

Figure 2-2 Overview of potential rebound effects at micro-, meso-, and macro-level

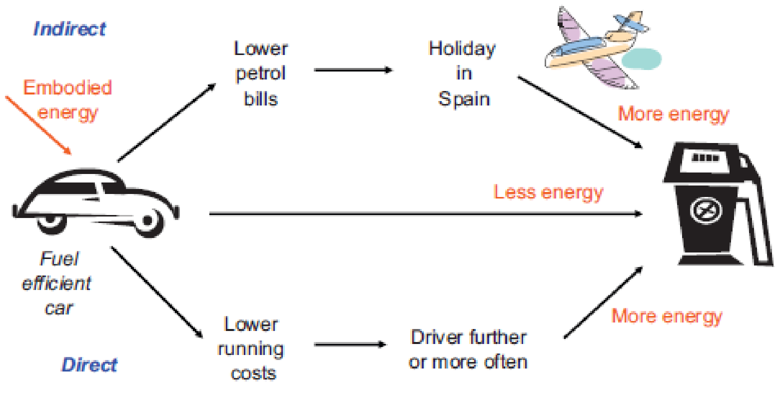
1) Micro-level rebound effect

In the micro-level, two pathways have been considered, direct and indirect effects. Direct rebound effect focuses only on the single energy service at the microeconomic level, which denotes the increased energy consumption stemming from the energy cost reduction (Santarius, Walnum, & Aall, 2016: 6; Maxwell et al., 2011: 6). On the other hand, the indirect rebound effect includes the impacts of different energy services, instead of the single same energy sector, and refers to the additional consumption of other products and services derived from the cost-savings and increased budget availability (Santarius et al. 2016: 6; Maxwell et al., 2011: 6).

Income effect: Since cost savings actually have the same effect as income increases, consumers and firms may respond to the increase in income by changing their behaviour in such a way that it increases energy use (e.g. more travelling). This is called 'income effect' (Jenkins, Nordhaus, & Shellenberger, 2011: 13).

Substitution effect: At the same time, consumers may use more energy due to the relatively cheaper energy price. They may replace goods, devices or services by other goods or services with more energy use (e.g. replace a classic bicycle by an e-bike), generating direct rebound effects. Similarly, firms may use more energy service by changing production processes, requiring a higher energy input. These are called 'substitution effects' (Jenkins, Nordhaus, & Shellenberger, 2011: 13; Santarius, 2016a: 408; Maxwell et al., 2007: 33-34).

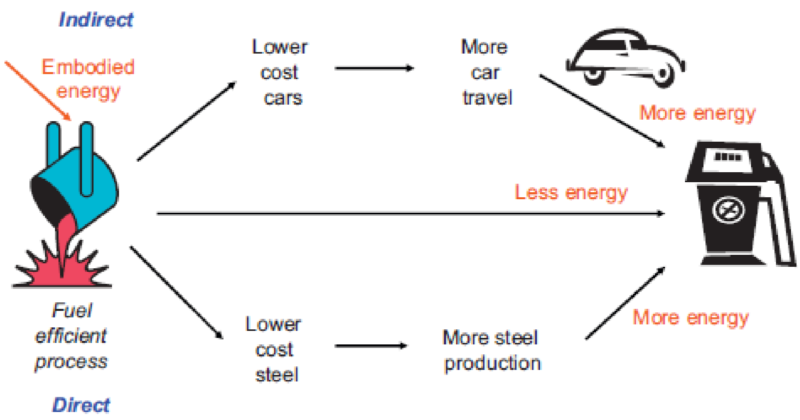
Figure 2-3 shows an example to illustrate the mechanisms of direct and indirect rebound effect in the case of fuel efficiency improvements. When car owners buy a more fuel efficient car, they can save fuel costs. Direct rebound effect refers to the situation that car owners spend the cost savings on driving more kilometres. In addition, the saved costs can also be used to buy a flight ticket for long-distance travel, which may offset the energy savings by improvement in fuel efficiency or may spend more energy than before. This is classified as an indirect rebound effect (Sorrell, 2009).



Source: Sorrell (2009). p1458.

Figure 2-3 Illustration of rebound effects for consumers

Both direct and indirect rebound effects can arise not only at the consumer-side but also at producer-side in the process of production by firms (see Figure 2-4). For instance, more fuel-efficient process of steel-making allows producers to lower the costs of steel production and it can let the steels sold at a cheaper price in the market. The lowering price of steels can increase sales, and in turn, this might lead to more quantity of steel produced, consuming more energy. This is referred to a direct rebound effect. At the same time, the fuel-efficient process of steel-making may lower the price of cars. Producers might spend the saved cost from the car purchase on more car travel, which requires more energy than before. This is considered as an indirect rebound effect (Sorrell, 2007; 2009).



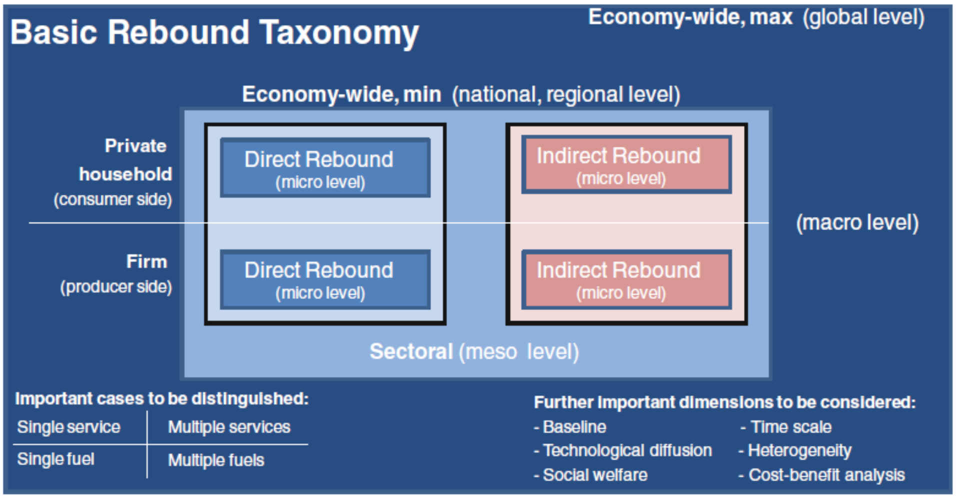
Source: Sorrell (2009). p1458.

Figure 2-4 Illustration of rebound effects for producers

2) Meso-level and Macro-level rebound effect

Figure 2-5 presents basic rebound taxonomies from micro- to macro-level in the whole economy. The interaction between consumers and producers at micro-level in the market can influence the energy price at industry sectors. If the price goes down, higher energy demands would be fostered. Such effects are denoted as 'Meso-economic rebound effect' (Santarius, Walnum, & Aall, 2016: 6). Furthermore, micro-economic and meso-economic rebound effects at consumers and industry level can be aggregated at macro-level, which is classified as 'Macro-economic rebound effect' (Madlener & Turner, 2016).

In the picture, all types of rebound effect are interconnected to each other. Overall economy-wide rebound effect can be derived from micro- to macro-level, including both direct and indirect rebound effects with complex socio-economic mechanisms. Therefore, 'Economy-wide rebound effect' implies the overall effect reflecting every level of rebound effects aggregated by sum up sub-effects all together (Maxwell et al., 2011: 6; Santarius, Walnum, & Aall, 2016: 6).



Source: Madlener and Turner (2016). p20.

Figure 2-5 Rebound taxonomy

At the meso-level and macro-level, several rebound generating mechanisms have been identified, such as re-investment effect, embodied energy effect, market price effect and economic growth effect.

Re-investment effect: The cost saving from the energy efficiency improvement can also cause indirect rebound effect at meso-level through the re-investment effect. Firms may invest the savings to increase the output of their products, which may increase energy demand as well as other production inputs such as materials, capital, and labour. The increased demand for production inputs, in turn, may lead to a further increase in energy demand. This is called 're-investment effect' (Jenkins, Nordhaus, & Shellenberger, 2011: 13; Santarius, 2016a: 407).

Embodied energy effect: When energy efficient equipment is used in the production processes, this will require energy to install and to manufacture the equipment. Similarly, investment and innovation in technology to improve energy efficiency also itself requires energy. This embodied energy may offset the energy savings, generating rebound effect (Sorrel, 2009: 1457; Santarius, 2006a: 408; Jenkins, Nordhaus, & Shellenberger, 2011: 13).

Market price effect: The aggregated effects from micro- and meso-economic level can cause macro-economic rebound effects. Widespread improvement in energy efficiency can cause large-scale reductions in energy demand. It may contribute to lower energy prices. The decrease in market price will increase real income and it may encourage more use of energy services inducing rebound effects. This is defined as 'market price effect' (Santarius, 2006a: 409; Sorrell, 2009: 1457; Jenkins, Nordhaus, & Shellenberger, 2011: 13).

Economic growth effect: Aggregated impact of micro and macro rebound effects on an economy can results in the increase in overall energy productivity of the economy. The increased productivity intrigues a higher level of economic outputs, increasing the energy demand. This is called 'economic growth effect' (Jenkins, Nordhaus, & Shellenberger, 2011: 13; Freeman, Yearworth, & Preist, 2016: 343).

2.3.2 Social practice theory

1. Basic assumption

Social practice theory has sought to understand human activities in the relationship with socio-technical structures (Sonnberger and Gross, 2018). Instead of focusing on individual choices and intentions, social practice theory posits that "institutional, infrastructural, and cultural structures play a strong role in shaping social action, understood as a constellation of practices rather than the result of individual attitudes and values" (Kennedy, Cohen, & Krogman, 2015: 4). In this context, the practices are defined as the routinized types of human behaviours that construct everyday life in society (Reckwits, 2002: 249). They can be recognized as the bundle of activities across space and time such as cooking, shopping, traveling, and washing. In social practice theory, such practices are the basic unit of analysis, rather than individual decisions.

From the perspective of social practice theory, rebound effects are attributed to the evolution of social practices stemming from the improvements in energy efficiency. Using energy efficient devices and machines can affect the individuals' time availability and the size of accessible geographical and functional space, which changes people's lifestyle and may increase possibilities to consume more energy than before. Relying on this perspective, social practice theory has started the investigation on the rebound mechanisms from the questioning of how social practices emerge, persist, and disappear due to the efficiency improvements. It claims that the emergence and evolution of practices can be the source of constructing individuals' behaviours and inducing structural rebound effects (Warde, 2005: 140; Sonnberger & Gross, 2018).

2. Rebound generating mechanism

Regarding the increase of efficiency, social practice theory tends to focus on the time dimension rather than money or energy itself (Wallenborn, 2018). This is because the efficient use of energy within daily practices can be identified as the use of efficient devices or machines and it often allows people to save time. Rebound effects may arise when the saved time is used again to perform more / different activities consuming energy (Shove, Watson, & Spurling, 2015).

Rebound effects can arise when the improvement in energy efficiency enables more activities during the same period of time or allows expansion of space for the activities, which may increase energy use. Both time-saving and space-connecting serve as a driving force to the evolution of social practices, leading to the rebound effects. Furthermore, the perspective of social practice theories on rebound effects have emphasised the structural mechanisms of generating rebound effect in relation with on the one hand social norms and on the other hand the availability of physical infrastructure to perform activities in the geographical space, accelerating the speed of change in social life (Sonnberger, & Gross, 2018; Wallenborn, 2018; Labanca, & Bertoldi, 2018). This can be explained as follows.

1) Changes in social practices

Changes in social practices caused by the enhancements of energy efficiency are considered as core mechanisms to generate rebound effects. Efficiency improvements cause changes in time-space frames for the activities of individuals, households and firms, leading to changes in social practices. As the efficiency of one practice increases, the other practices are also affected because many practices are inter-related and co-dependent. Through these changes, overall patterns of daily routines can be restructured, which may be the main factor that generates rebound effects (Sonnberger & Gross, 2018).

In social practice theory, two possible pathways have been identified in which rebound effects occur: Dispersion and Integration (Wallenborn, 2018). Dispersive rebounds arise when new social practices emerge or existing practices which were previously integrated are disconnected. The dispersion of practices can appear where saved time in one practice is used to perform other useful activities, leading to more energy use. On the other hand, integrative rebounds can occur where efficient devices enable connecting different social practices across time and space. For instance, increased car fuel efficiency can combine different activities to car-driving, such as commuting, shopping and travelling, while keeping the budget under control. Using a car allows saving time as well as more convenience for doing those activities comparing to doing each separately, which can speed up of life and lead to more activities within the same time frame which can result in an increased overall fuel consumption (Wallenborn, 2018; Sonnberger & Gross, 2018).

Both dispersion and integration of practices are dynamic processes, which evolves in relation to physical infrastructure and social norms. The co-evolution processes can amplify the magnitude of rebound effects over time (Shove, 2017; Sonnberger & Gross, 2018).

2) Infrastructure

Infrastructure plays a role of offering physical resources for social practices and it serves as a provisioning system (railways, roads, communication, and energy networks). In general, there exists a recursive relation between a persisting practice and infrastructure. Where the efficiency of specific practices improves, the practices can spread and further expand in society, leading to more construction of necessary infrastructure. This co-evolution of practices and infrastructure may result in the status of structural lock-in since the system of infrastructure once formed is irreversible. Because the structural lock-in reinforces the spread of certain practices over time and space, rebound effects are highly likely to occur. The position of the practices in our life (geographical and time patterns) becomes more robust and less likely to be replaced by alternative practices due to the infrastructure already constructed (Unruh, 2002; Seto et al., 2016).

An example can be found in the car driving practice and the relationship between automobile usage and road networks. The more automobiles use the roads, the larger the pressure to expand the road networks to meet the traffic demand. The expansion of roads encourages car owners to drive more kilometres for bridging the spatial distance between different locations. At the same time, it promotes more purchase of cars, since car driving enables people to have more autonomy and flexibility regarding the performance of activities in space and time. These processes stimulate the increase of automobile use. Eventually, because of increased automobile usage, more congestion would occur again. These processes support the on-going expansion of road networks and car-dependent lifestyle, which has been mentioned as a critical factor of amplifying rebound effects by social practice theory (Urry, 2004; Duranton & Turner, 2011).

3) Social Norms

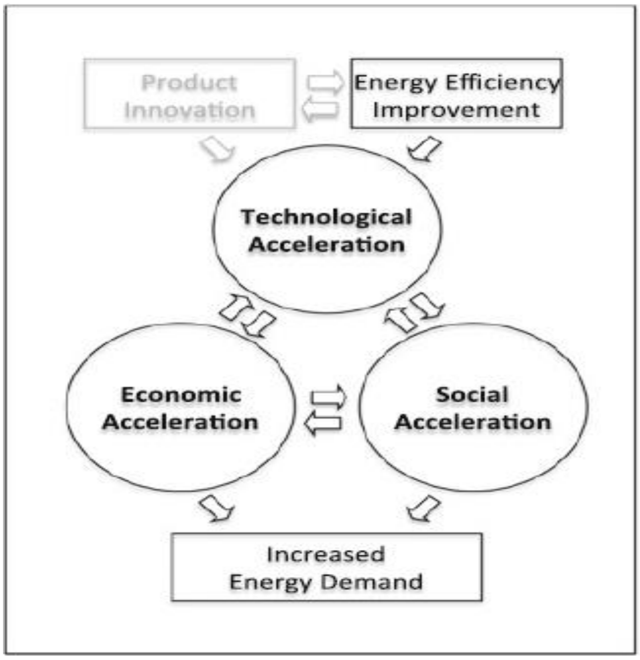
Social norms influence people's ideas about what are normal statuses. As social practices change with the efficiency improvements, the expectations about the practices' outcome, such as level of comfort, convenience, and cleanliness, etc., can also be increased, which may result in more time spending on the activities and strengthening energy intensive lifestyle (Shove, 2003; Wallenborn, 2018; Sonnberger & Gross, 2018). For instance, upgrades in the cooling and heating system in buildings can lead to changes in social standards in terms of typical room temperature as well as clothing cultures. The clothing style adapts to room temperature and it can increase energy demand for more cooling and heating. Along with these processes, dependency on the cooling and heating system becomes even greater and energy-intensive lifestyle can be established more firmly as part of life (Walker, Shove, & Brown, 2014).

4) Acceleration of everyday life

Improving energy efficiency enables people to achieve more tasks during a given period of time. Due to efficiency improvement, more practices can be squeezed into the limited amount of time and the pace of production and consumption can become faster. This increased speed of everyday life accelerates the rate of social change, which may result in rebound effects in energy demand (Shove, Trentmann, & Wilk, 2009; Rosa, 2013; Santarius, 2016b).

Such acceleration can be further specified into three types: Technological, Economic, and Social acceleration (Rosa, 2013; Santarius, 2016b). Figure 2-6 shows the causal relationship between the three, which is also denoted as a 'self-accelerating spiral' (Rosa 2013) because the technological acceleration induced by the energy efficiency improvement can propel the economic and social acceleration and those influences reinforce themselves, increasing energy demand.

In this spiral, the efficiency improvement in energy services can contribute to reducing energy inputs as well as time for activities. However, at the same time, the technical acceleration serves as a driving force for economic and social acceleration. These interactions clearly demonstrate the structural mechanisms of how and why rebound effects occur from the improved energy efficiency. Even though improved energy efficiency can contribute to less energy use and less time consumption, the positive gains may be fully or partially offset by the processes of economic and social acceleration (Santarius, 2016b).



Source: Santarius (2016b). p156.

Figure 2-6 Causal loop of the structural rebound effect

2.3.3 Possibility of integrating two theoretical approaches

Based on the reviews on economic theory and social practice theory in the previous sections, Table 2-1 summarises and compares the two perspectives on rebound effects at a glance. Each theory seems to have its own lens to view the phenomenon of rebound effects. The economic theory understands the rebound phenomenon based on individual decisions to maximize utility and profits. Social practice theory takes a different lens and understands the rebound phenomenon as an accumulation of time-space changes in social practices of everyday life.

Table 2-1 Comparison of two theoretical approaches to rebound effects

	Economic theory	Social practice theory
Underlying assumptions	- Individuals are eager to maximize their utility and profits - The economy is as a system composed of individuals and their choices	- Recursive interaction with socio-technical structure determines human behaviours - Social practices, the pieces of routinized activities, are delivered by individuals
Source of rebound effects	- Changes in individual choices in the market.	- Evolutions of social practices in everyday life
Rebound pathways	- Direct and Indirect	- Integrative and Dispersive
The main focus of analysis	- Cost (money) saving - Changes in price and real income	- Time-saving - Changes in practices across time and space
Amplifying forces	- Market price - Economic growth	- Social norms and Infrastructures - Acceleration of social change

Source: by author.

Although each theoretical view has started the investigation of rebound effects based on different assumptions, both seem to commonly accept the dynamic characteristic of the processes arising rebound effects. Economic theory has been interested in individuals' cost-saving effects first but more importantly, it has traced the processes of aggregating effects of the cost-savings in the economy through the price mechanism and returning the impact of the price change on the individuals. Social practice theory describes the recursive interactions between social practice evolutions, and norms and infrastructures. Also, it has presented the interconnection among technical, economic, and social changes and demonstrated that they accelerate the speed of changes by interacting with each other (Santarius, 2016b).

The integration of these dynamic mechanisms demonstrated in economic theory and social practice theory can broaden the understanding of rebound generating mechanisms. As already shown in Figure 2-6, economic change and social changes are influenced by each other. By converging two perspectives, the dynamics of arising rebound effects in the economy and society will become more concrete, which could contribute to theoretical development in this topic.

2.4 How small or large is the rebound effect?

Most methodologies to estimate the magnitude of rebound effects have been applied by scholars in the field of energy economics. Table 2-2 presents the methodologies to analyse rebound effects by rebound type. The methods heavily rely on price elasticity estimation and econometric modelling. Also, Computable General Equilibrium (CGE) models have been utilised for economy-wide rebound estimation (Maxwell et al., 2011).

Table 2-2 Estimation methods of rebound effects

Rebound type	Method of analysis
Direct	Micro-econometric modelling of households/producers, including estimating price elasticities, income elasticities, etc.
Indirect	Micro-econometric/Macro-econometric modelling of households/producers: estimation of cross-price or substitution elasticities (impact of a change in the price of one factor/good on the demand of the other factor/good)
Economy-wide	Macro-econometric models (often estimate behavioural relationships within an input-output structure) or Computable General Equilibrium (CGE) models

Source: Maxwell et al. (2011). p34.

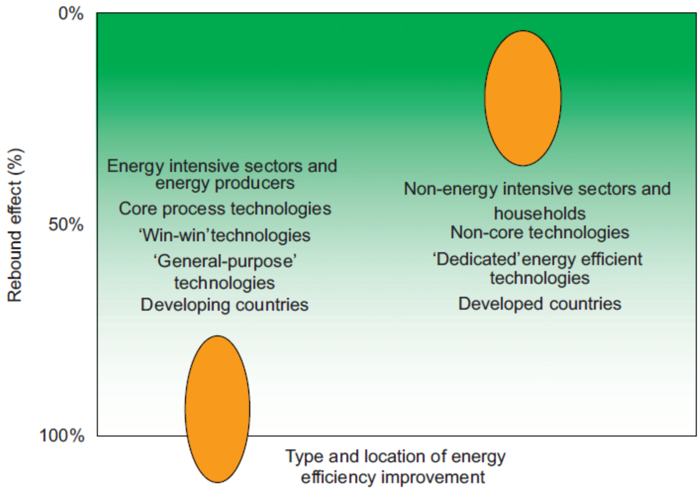
The magnitude of rebound effects, however, is still a controversial issue, despite the estimations in previous research (Sorrell, 2007; Michaels, 2012; Chakravarty, Dasgupta, & Roy, 2013; Vivanco et al., 2016). This is attributed to the fact that previous estimations on the magnitude of rebound effects had a large variation from 15% to 350% (Dimitropoulos, 2007). Table 2-3 shows the summary of the results of previous estimations, analysed by the CGE model.

Table 2-3 Summaries of characteristics of and results from CGE studies

Author/Year	**Country**	**Production Function**	**Elasticity of substitution (σ)**	**Efficiency %**	**Rebound %**	**Comments**
Semboja 1994	Kenya	Cobb Douglas – Leontief	1 or 0	1	170-350	Simulations for energy production and use
Dufournaud et al 1994	Sudan	Constant Elasticity of substitution	0.2-0.4	100-200	54-59	Households only, well structured, extensive sensitivity analysis
Van Es et al 1998	Holland	Constant Elasticity of substitution	$0<\sigma<1$	100	15	Bottom-up feed database, Explicit representation of efficiency improvements
Vikstrom 2004	Sweden	Constant Elasticity of substitution	0.07-0.87	12-15	60	Dynamic simulations with counterfactual efficiency changes
Grepperud & Rasmussen 2004	Norway	Constant Elasticity of substitution	$0<\sigma<1$	100 Average annual growth rates of energy productivity (per sector) Electricity or oil	<100	Dynamic simulations with counterfactual scenarios
Washida 2004	Japan	Constant Elasticity of substitution	0.3-0.7	1	35-70	Sensitivity analysis reveals positive relation of rebound with elasticity of substitution
Glomsrod&Taoyuan 2005	China	Cobb Douglas, Leontief, Constant Elasticity of substitution	1	Not available	>100	Focused on limiting emissions with a tax on coal use
Hanley et al. 2005	Scotland	Constant Elasticity of substitution	0.3	5	120	Open region approach with major energy exports
Allan et al. 2006	UK	Constant Elasticity of substitution	0.3	5	37	Extensive sensitivity analysis

Source: Dimitropoulos (2007). p6358.

The great differences among the estimations may be driven by the boundary setting of the estimated rebound effects or methodological differences (Van der Bergh, 2011; Irrek, 2011). Moreover, the magnitude of rebound effects varies by the type and location of implemented energy efficiency improvements. Figure 2-7 illustrates a general tendency that can influence the magnitude of rebounds between small and large. Generally, more energy-intensive sectors have greater rebound effects than non-energy intensive sectors. Also, developing countries are apt to face larger rebound effects than developed countries (Sorrell, 2009).



Source: Sorrell (2009). p1467.

Figure 2-7 Condition under which rebound effects may be large or small

Above all, estimation on rebound effects is a challenging task because the rebound creating mechanisms are part of dynamic processes, which take place over a long time period and it is hard to set a sharp boundary of the scope of impact. Particularly, indirect and economy-wide rebound effects appear more difficult to be assessed than the direct rebound effect, due to the existence of the ambiguous boundary and the complexity of tracing the causal relationships of emerging rebound effects (Irrek, 2011).

2.5 How to mitigate the rebound effect?

Research addressing the mitigation strategies of rebound effects has been fairly scarce. Only a few studies present assessments on pricing mechanisms such as energy and carbon taxation. They argue that an appropriate level of tax imposition can be an effective solution to mitigate rebound effects from both consumer-side and producer-side (Sterner & Coria, 2013).

More comprehensive policy options applicable for the rebound mitigation have also been suggested by a few publications (Van den Bergh, 2011; Maxwell et al., 2011; Vivanco et al, 2016). Table 2-4 shows the list of suggested policy options with their policy pathways for the implementation of each class of strategies. Five types of policy pathways have been indicated: Policy design, Sustainable consumption and behaviour, Innovation, Environmental economic policy, New business models. These proposals, however, seem to be more comprehensive policy measures for general environmental management than targeted policy intervention to reduce rebound effects based on the analysis of rebound generating mechanisms.

Table 2-4 Policy pathways and options for rebound mitigation

Type of policy pathways	Policy options for rebound mitigation
Policy design	- Recognition in policy design - Broader definitions and toolkit - Benchmarking tools
Sustainable consumption and behaviour	- Consumption information - identity signalling - Standardisation - Autonomous frugal behaviour
Innovation	- Targeted eco-innovation
Environmental economic policy	- Energy/carbon tax - Bonus-malus scheme - Cap and trade scheme
New business models	- Rebates and subsidies - Product service systems

Source: Vivanco et al. (2016). p118.

Chapter 3. Research Methodology

3.1 System dynamics modelling

System dynamics is a methodology of analysing a complex system that changes over time. It aims to understand problematic behaviour arising from the dynamics of the complex system. The problematic behaviour often means an unintended or unanticipated consequence. The purpose of system dynamics modelling is to enhance the understanding of the complex dynamic mechanisms producing the problematic behaviour and to control the system in a more desirable direction (Ford, 2010: 6-8).

System dynamics develops models to organise major system structures creating problematic behaviour by giving attention to information flows, physical and information accumulation, time delays, nonlinearity, and feedback loops. Because the models often have complex causal relationships in which time plays as an important factor, system dynamics relies on computer modelling and simulation. The simulation enables to overcome the limitations of human's information processing ability and bounded scientific reasoning (Sterman, 2010: 34-39).

This study applies system dynamics as a research method to analyse the socio-economic mechanisms generating the rebound effects. Rebound effects from the improved energy efficiency were considered as an unintended outcome from the dynamics of the socio-economic system. System dynamics modelling and simulation allows for exploring possible futures of rebound effects, which enhances the understanding of the rebound mechanisms.

3.1.1 Deductive approach to model building

According to Größler and Milling (2007), system dynamics modellers may choose an approach to the model building processes between inductive and deductive modelling. Inductive modelling aims to investigate a specific management problem to support the involved decision makers or stakeholders, whereas deductive modelling is more appropriate for research that aims to test theory-based hypotheses. The target audience modelling tends to be academia, aiming to find missing knowledge on a phenomenon (Größler and Milling, 2007: 1).

The system dynamics modelling in this study takes a deductive approach to the model building. The modelling investigates the earlier discussed rebound phenomenon. Pre-existing theories offer the grounds for the model formulation; however, the system dynamics model integrates different theoretical point of views to rebound effects. It synthesizes economic and social practice theories on rebound effects, translating the complex mechanisms in the form of causal structures building the model.

System dynamics modelling is fundamentally interdisciplinary because it roots in a practical analytic strategy to investigate real-world complex problems (Sterman, 2010: 5). The modelling aims to capture the underlying causes of the problematic behaviour. Therefore, diverse knowledge, voices, and perspectives should be delivered in the model, if it can influence the system behaviour. As adopting this practical point of view, system dynamics enables to combine different disciplines, overcoming the differences in philosophical foundations and the incommensurability of various concepts.

3.1.2 Modelling processes

The processes of system dynamics modelling generally consist of several steps such as problem articulation, setting dynamic hypothesis, model formulation, model testing, and policy formulation and evaluation. These steps are regarded as iterative learning processes, rather than sequential processes (Sterman, 2010: 87; Ford, 2010: 158-162).

Table 3-1 informs on the more detailed steps of the system dynamics modelling process (Ford, 2010: 149). The modelling of this study also followed these eight steps to developing the system dynamics model of rebound effects with recursive reflections.

Table 3-1 The steps of system dynamics modelling

Step 1.	Acquainted with the problem
Step 2.	Be specific about the dynamic problem
Step 3.	Construct the stock-and-flow diagram
Step 4.	Draw the causal loop diagram
Step 5.	Estimate the parameters
Step 6.	Run the model to get the reference mode
Step 7.	Sensitivity analysis
Step 8.	Testing the impact of policies

Source: Ford (2010). p149.

The first step in the modelling processes is to become familiar with the problem. In this step, one needs to learn about various views of the problem. The second step is to define the dynamic problem. A time-graph of a critical variable can show the problem targeted by the modelling, which is called 'reference mode'. The third step is to construct the Stock-Flow Diagram (SFD). The fourth step is to draw the Causal-Loop Diagram (CLD). Both SFD and CLD are called 'dynamic hypotheses' because the model structures show a possible idea about the underlying causes generating the problematic behaviour. The structures will be further analysed and tested in the following steps. The SFD serves as an analytic tool for the simulations whereas the CLD is used for communication presenting major causal structures in the model (Ford, 2010: 149-152).

The fifth step is to estimate the parameter values in the model. In this step, all available information should be considered as the input data, not only the numerical database but also databases including written data and possibly tacit knowledge and expert judgements. The sixth step is to run the model and start the model testing whether the simulated outputs accurately shows the reference mode. The seventh step is to conduct sensitivity analysis, which tests whether the model results are sensitive to changes in the parameter values. The final step concerns the policy analysis in which a range of input values are assigned to the policy variables and the model is run several times to find the most promising policy (Ford, 2010: 152-158).

3.2 Specifying a sector of analysis

3.2.1 Automobile fuel efficiency

The system dynamics modelling on rebound effects in this study centres on the sector of automobile fuel efficiency in the EU countries. Automobile fuel efficiency, also known as fuel economy, is defined by the distance travelled per unit of fuel consumed by a vehicle (Small & Van Dender, 2007). It conceptually refers to the energy efficiency of the automotive sector, where the energy input means the amount of fuel and the output is kilometre distance travelled. However, in practice different indicators are presently used, notably the following ones.

Energy efficiency is expressed by the indicator of miles per gallon (MPG) in America. On the other hand, the litres per kilometres (L/100km) equal the typical indicator for fuel efficiency in Europe. The latter one can also be called energy intensity as the inverse of energy efficiency. Furthermore, the fuel efficiency can be converted into the range of indicators such as joule per kilometres (kJ/km), cost per kilometres ($/km), or CO2 emissions per kilometres (CO2/km).

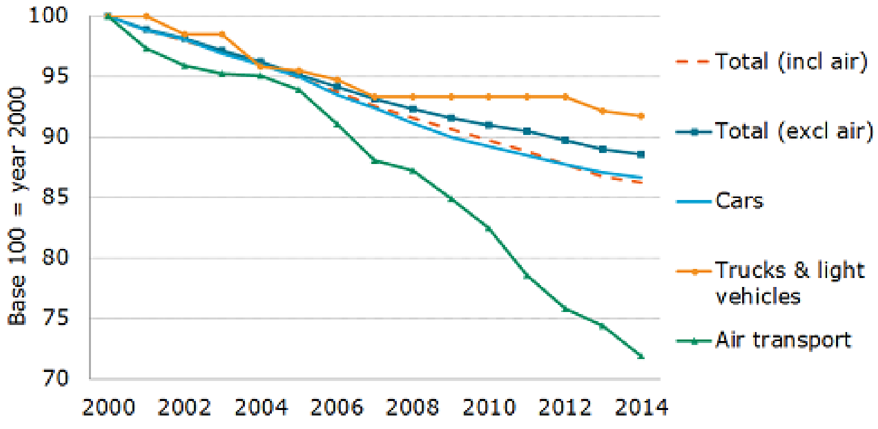
In building the model in this study, the fuel efficiency was denoted by the litres per unit kilometres (L/km). On the other hand, final energy consumption, derived from fuel use by automobiles, took the indicator of joule (J) or tera-joule (TJ), rather than liter (L) or ton. This is because the databases of energy consumption in the EU mostly report the energy consumption in terms of joules.

The transport sector has the highest portion of the total energy consumption among the energy sectors in the EU as well as worldwide (ODYSSEE, 2017; IEA, 2018). In particular, road traffic, mainly due to the use of cars for passenger transport, has been increased significantly over the decades, which has led to significant increases in CO2 emission. Fuel efficiency has been proposed by the EU as one of the solutions for reducing energy consumption as well as CO2 emission. Currently, the EU's policies seek to enhance the fuel efficiency standards for new vehicles to reduce CO2 emission from passenger cars (European Environment Agency, 2017).

The sector of automotive fuel efficiency can also be a suitable sector of analysis in the aspect of theoretical integration of rebound effects. Previous works of literature on rebound effects has focused on the improvement in automobile fuel efficiency, both from the fields of economic theory and social practice theory (Small & Van Dender, 2007; Shove, Watson, & Spurling, 2015; Mattioli, Anable, & Vrotsou, 2016; Freeman, Yearworth, & Preist, 2016; Stapleton, Sorrell, Schwanen, 2016), offering pieces of work that can be used to build on in this study.

3.2.2 Trends of transport energy efficiency and energy consumption

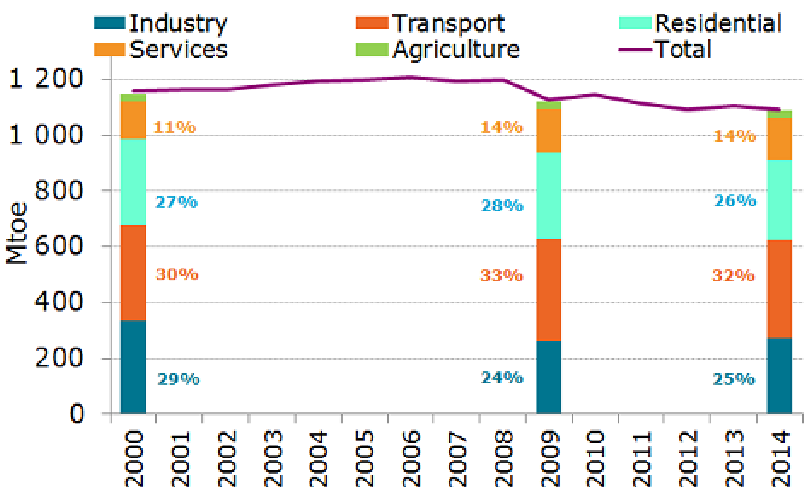
According to ODYSSEE (2016), the energy efficiency of transport in the EU has improved by about 13% between 2000 and 2014 in which passenger cars, air transport, trucks, and light vehicles are counted (see Figure 3-1). Air transport had the highest improvement rate, followed by passenger cars, and truck and light vehicles. The fuel efficiency of passenger cars improved by about 1% per year in the same period.



Source: ODYSSEE (2016).

Figure 3-1 Energy efficiency (energy consumption per unit of distance travelled) progress in transport in the EU

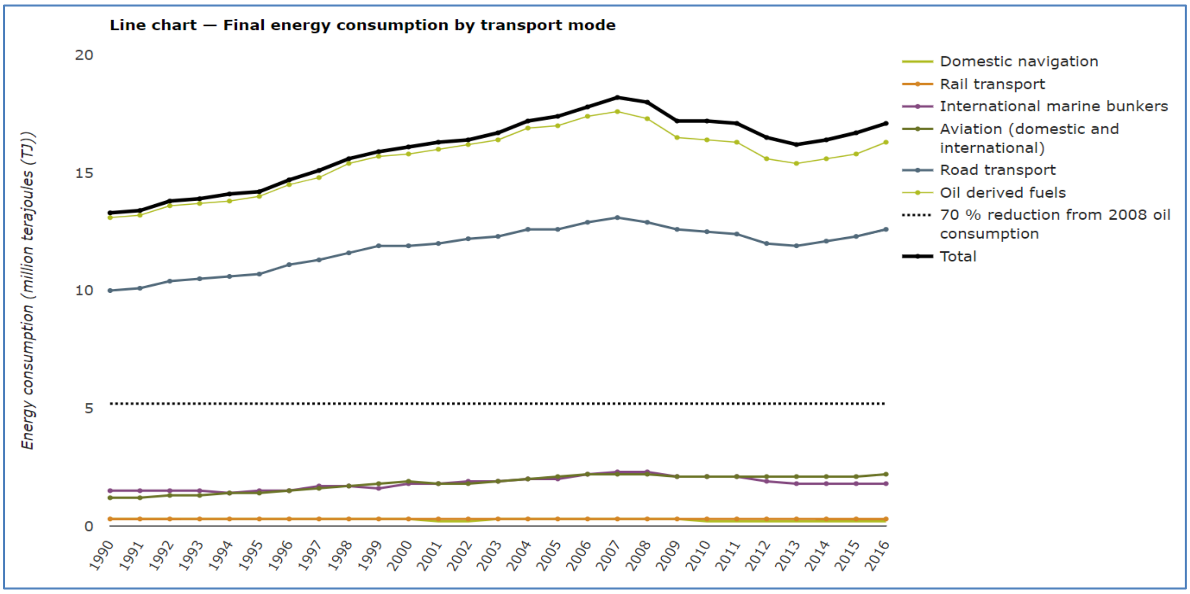
Notwithstanding the enhancement in fuel efficiency, the energy consumption of transport took a large portion, around 30~33% of total energy consumption in the EU, summing up to about 1100 Mtoe in 2014 (see Figure 3-2). The rest of the sectors showed lower percentages of total energy consumption: Industry (24~29%), residential (26~28%), services (11~14%) between 2000 and 2014 (ODYSSEE, 2017).



Source: ODYSSEE (2017).

Figure 3-2 Final energy consumption in the EU (normal climate)

Figure 3-3 shows the historical trend of final energy consumption by transport mode in EEA-33 countries. Although there was a decline in energy consumption between 2007 and 2013, the overall annual energy consumption of transport increased by 34% between 1990 and 2016. Also, road transport accounted for the highest portion, 74% of the total energy consumption by transport mode in 2016. Despite the decline in energy consumption between 2007 and 2013, the amount of energy consumption by road transport in 2016 was 32% higher than in 1990. The downward trend between 2007 and 2013 has been explained by the European authorities as an outcome driven by the economic recession (European Environment Agency, 2018).



Source: Eurostat; Graph produces by European Environment Agency (2018).

Figure 3-3 Energy consumption by the European transport sector (EEA-33 countries)

3.2.3 EU's initiative to increase automobile fuel efficiency

The EU's 2030 Climate and Energy framework set out key targets for 2030, which included a 40% reduction in greenhouse gas emission from 1990 levels and a 32.5% improvement in energy efficiency. The 2030 targets were originally adopted by the European Council in 2014 and revised upwards in 2018 (Website of European Commission[2]). Concerning to transport sector, the EU adopted

[2]The contents referred from https://ec.europa.eu/clima/policies/strategies/2030_en.

two targets to reduce CO_2 emission, a 20% reduction from 2008 levels by 2030 and a 60% reduction from 1990 levels by 2050 (Website of European Commission[3]).

The EU gave attention to road transport to achieve these goals, which accounts for about 84% of the total CO_2 emission stemming from transport (European Commission, 2001:10). The policy strategies to tackle the CO_2 emission aim to less oil dependency of transport fuel, by using alternative fuels and by improving the fuel efficiency of road vehicles (European Commission, 2001: 10).

The improvement in fuel efficiency of vehicles has been implemented since 2009, by the regulations on the fuel efficiency and CO_2 emissions of new cars and vans. The EU set targets for reducing the CO_2 emission for new cars and vans, which included a 40% reduction in CO_2 emission from new cars in 2021 as compared to 2005 and a 19% reduction for new vans in 2020 as compared to 2012 (Website of European Commission[3]).

[3] The contents referred from https://ec.europa.eu/clima/policies/international/paris_protocol/transport_en

Chapter 4. Model formulation

4.1 Reference mode

The modelling exercise in this study aims to understand socio-economic mechanisms generating rebound effects from the increased energy efficiency. The targeted dynamic behaviour of the modelling is the changes in the total aggregated energy consumption from driving automobiles over time within Europe. The time-graph of energy consumption in Figure 4-1 serves as reference mode for the modelling.

In spite of the enhancement in fuel efficiency, energy consumption might not follow the trends that expect energy savings and fuel consumption reductions from increased fuel efficiency. The gap between the expectation and the actual energy consumption indicates the fact that there exist rebound effects (see Figure 4-1). Moreover, if the energy consumption becomes higher than the baseline projection, it means that backfires occur. The red dot-lines in the graph below illustrate the problematic behaviours targeted by the system dynamics modelling.

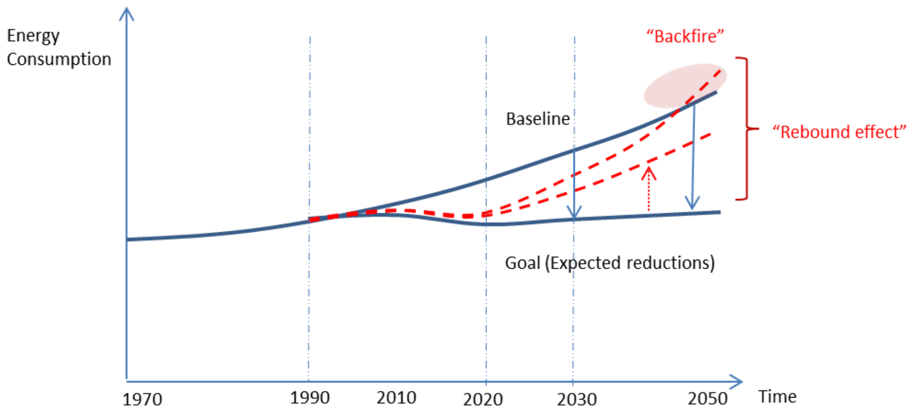


Figure 4-1 Reference mode of the model

The model does not concentrate on the estimation of the specific magnitude of the rebound effect. Rather, it aims to enlighten the future trends in energy consumption and the possibility that backfire effects occur.

The horizontal axis of the reference mode shows the time period adopted for the model analysis. It should be sufficiently long so that the model is able to produce meaningful results reflecting the dynamics of the underlying structures in the system (Ford, 2010: 150).

This study used a time horizon from 1970 to 2050. The data from 1970 to 2017 served for the model testing and calibration. Next, the calibrated model ran for the period from 2010 to 2050 to see future trends of energy consumption. This time horizon for the model analysis was set to reflect the timelines of policy targets in reality. For example, the EU's policies for the improvement in energy efficiency and the reduction in CO2 emission target for the year 2020, 2030, and 2050.

4.2 Model boundary

Models address a specific problem, rather than they mimic the whole system (Sterman, 2010: 86). The model boundary allows more clear explanations on the dynamic problems focusing on the underlying causes of them, enhancing learning and comprehensiveness.

The model of this study particularly focuses on automobile fuel efficiency and fuel consumption among various energy sectors to understand the rebound effects from the improve energy efficiency. Figure 4-2 presents the bull's-eye (Ford, 2010: 139), showing the model boundary of the study. In the diagram, key-variables are in the centre and the variables located outsides of the circle are excluded. These choices are based on the following considerations.

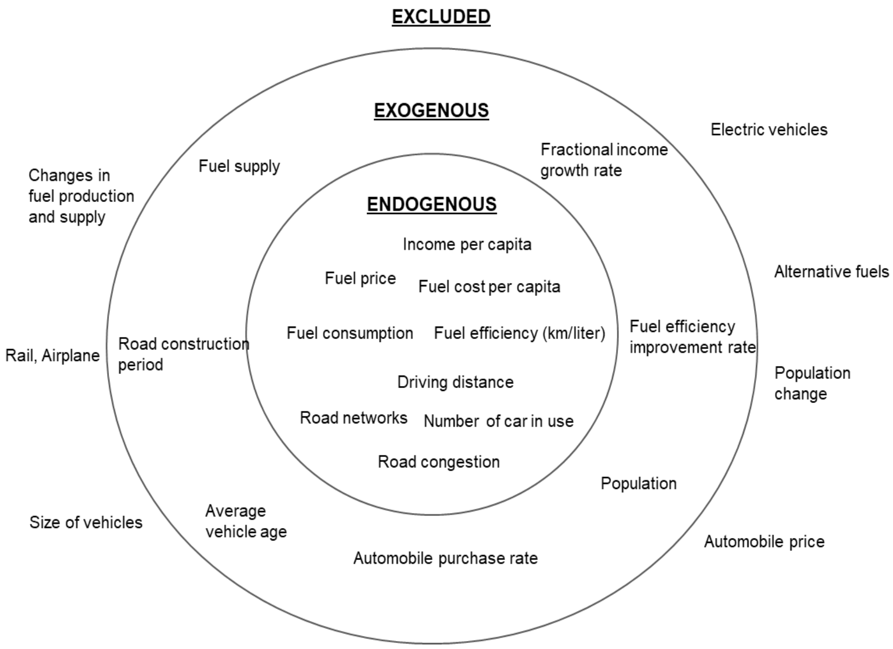


Figure 4-2 Bull's-eye diagram for model boundary

There are three categories of variables for setting the boundary of the model: Endogenous, Exogenous, and Excluded. Endogenous variables indicate the variables derived from inside the system, mainly by feedback loops. The endogenous variables of the model include fuel consumption, fuel efficiency, fuel price, income per capita, fuel cost per capita, driving distance, road congestion, length of road networks, and the number of vehicles in use.

Exogenous variables originate from outside the system, serving as input variables to the model. The exogenous variables of the model covered fractional targeted fuel-efficiency improvement rate, fractional income growth rate, average vehicle age, fuel supply and population.

Although the fuel supply and population have their own dynamics, they were kept outside the model boundary in order to simplify the potential dynamics. The assumption is that population will not change very much during the simulation period and the fuel supply will not suffer from structural shortages. It was assumed that the changes in fuel price are only affected by fuel consumption and energy demand rather than fuel production and supply. This simplification enables to better see the dynamics between energy consumption and the price. And, as mentioned, the model also simplified the dynamics of the population change over time. A fixed value of population is assigned as the input of the population variable. It enables the model to centre on the impact of the individual's fuel demand on total fuel consumption, excluding the influences of the size of the population on the aggregated amount of fuel consumption.

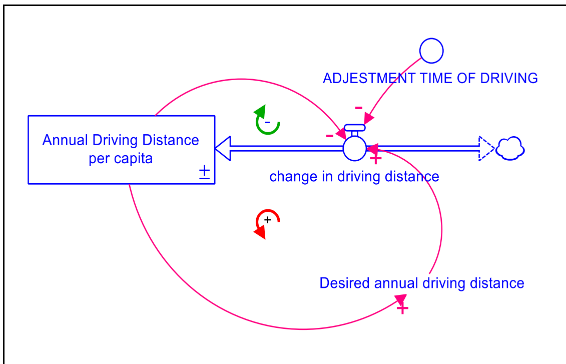
The purpose of the model is to see the dynamics between automobile fuel efficiency and energy consumption to understand the influence of rebound effects on energy savings and reductions. Since the model focuses on road transport, the model excluded rail and air transport. Also, the model did not deal with the influences of alternative fuels and the diffusion of electric vehicles because it only sought to analyse the effectiveness of the enhanced fuel efficiency on fuel consumption. Furthermore, the model did not consider the details in vehicle size and the dynamics of automobile price mechanisms. Including these additional variables and details would complicate the modelling dramatically, due to the required data and the increase of potential dynamics.

4.3 Dynamic hypothesis

Dynamic hypothesis means a potential explanation on the causes behind the problematic dynamics. It contains main model structures to show underlying causal relationships, including feedback loops, stock-flow variables, time delays, and nonlinear causality (Barlas, 2007: 19).

This study formulated the dynamic hypothesis, the model structure capable of generating rebound effects, step by step using stock and flow analysis, extending to causal relationships. It was formed first by the SFD and then simplified in the CLD. The SFD developed are based on the theoretical explanations on rebound mechanisms, suggested by the economic theory and social practice theory. The CLD support comprehension of feedback loops creating the rebound phenomenon.

The model structures developed from a stock, the annual driving distance per capita (km/year/person). The stock is adjusted by the changes in the desired annual driving distance with a time delay (see Figure 4-3). The stock parameter represents the behavioural responses by car-owners to the changes in fuel efficiency. This is because fuel consumption is calculated by multiplying the driving distance and fuel efficiency. When driving distance nonlinearly increases in reaction to the improvement in fuel efficiency, the rebound effect would occur.



Annual_Driving_Distance_per_capita(t)
= Annual_Driving_Distance_per_capita(t - dt) +
(change_in_driving_distance) * dt
UNITS: km/year/person

change_in_driving_distance = (Desired_annual_driving_distance
Annual_Driving_Distance_per_capita)/ADJESTMENT_TIME_OF_DRIVING
UNITS: km/year/person/years

Figure 4-3 Model structure of the adjustment in driving distance

After building the SFD in Figure 4-3, the critical question for the further development of the model structure arose*: What causes the changes in the desired annual driving distance?* Economic theorists answer to this question that the desired driving distance is affected by the effect of changes in fuel costs on the income of individuals. The model structure was therefore extended further to include the cost and income effect as presented in the SFD in Figure 4-4.

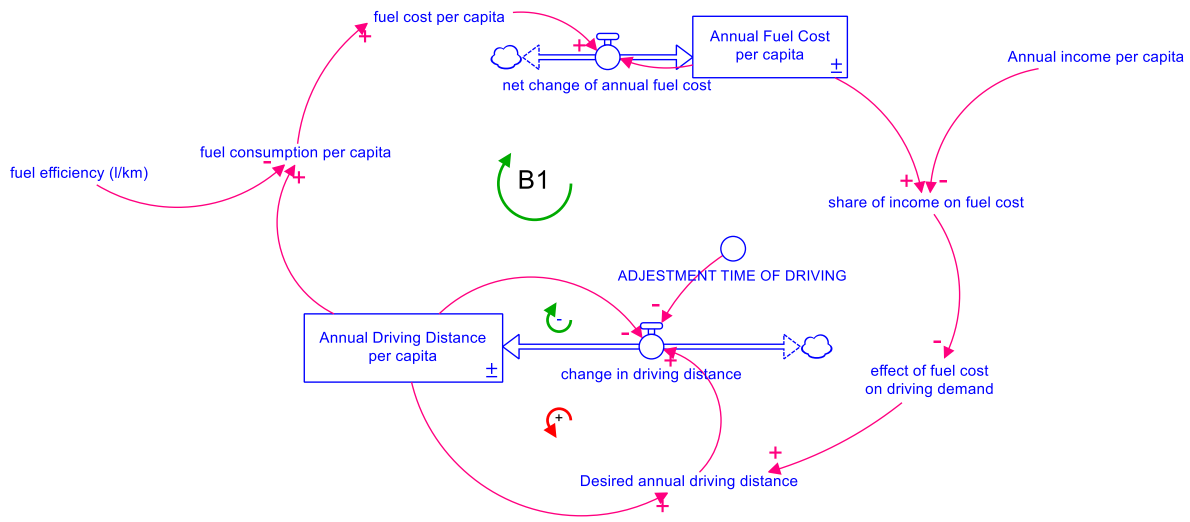


Figure 4-4 Balancing loop between driving distance and fuel cost

In the model structure, higher fuel efficiency can lower the fuel consumption per capita (in the early stages of time horizon), reducing fuel costs per capita. The decrease in the individuals' income share of fuel costs can lead to the increase of desired driving distances per capita. Consequently, the fuel consumption per capita increases again. This controlling mechanism represents a balancing feedback loop, B1.

The individuals' behavioural changes in fuel consumption can also induce an adjustment in fuel price at the macro-level. In return, the adjustment in fuel price affects the individual's fuel costs, influencing their desired driving distance. The existence of the multi-level interactions further extends the model structure.

Figure 4-5 displays the adjusted SFD, including the price change mechanisms at the macro-level of the economy. The balancing loop, B2, presents the regulating mechanisms of fuel price and fuel consumption at the macro-level. The fuel price can decrease by the reduction in the aggregated amount of fuel consumption from individuals. The lower price leads to lower fuel cost for individuals, which enables individuals to drive more kilometres, increasing the fuel demand again. The fuel price would be stabilised by the regulating mechanism of feedback loop B2.

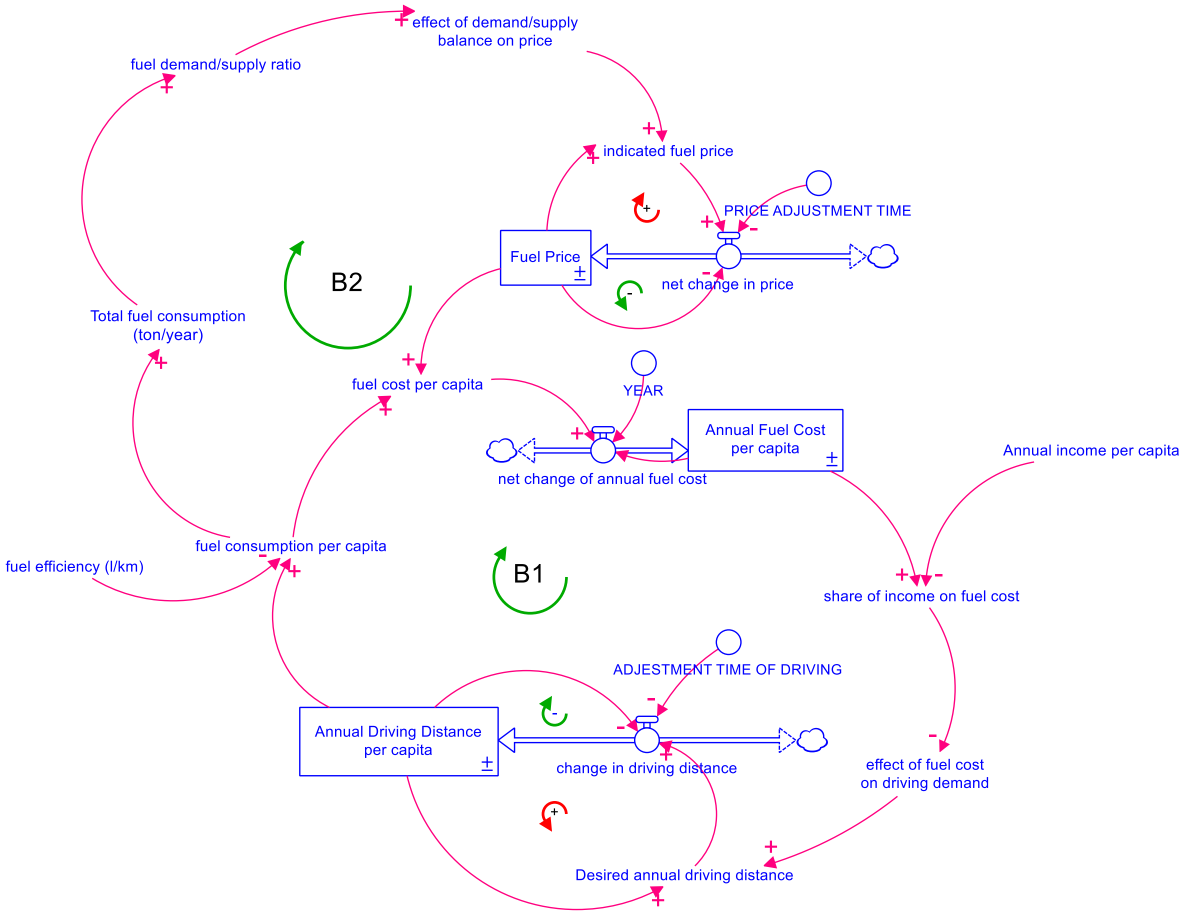
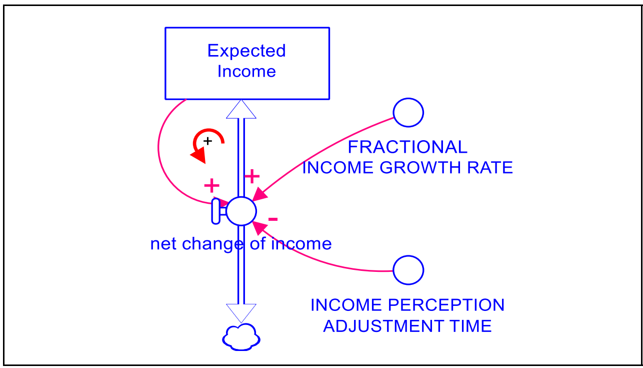


Figure 4-5 Balancing loop between driving distance and fuel price

Notwithstanding the balancing loops, B1 and B2, the historical level of fuel consumption and the nominal fuel price have increased over the decades. This might be due to the steady increase in income per capita. The annual income per capita influences to the share of income on fuel cost, located in the loops, B1 and B2.

The model includes a reinforcing loop to include the income growth mechanism, as has been expressed in Figure 4-6. In this model, GDP per capita serves for the annual income per capita. The positive feedback loop explains the historical trends of the growing economy and GDP per capita.



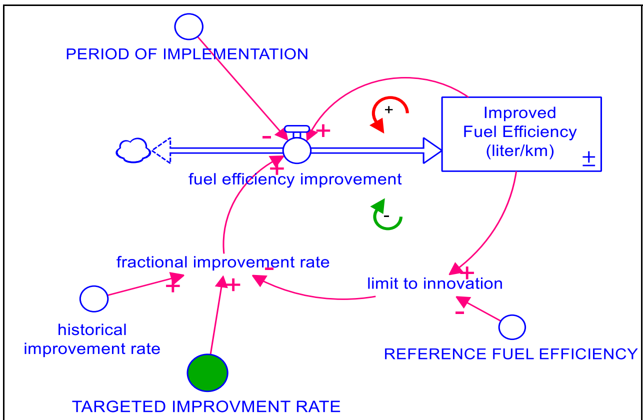
Expected_Income(t) = Expected_Income(t - dt) + (net_change_of_income) * dt
UNITS: Euro/year/person

net_change_of_income = (Expected_Income*FRACTIONAL_INCOME_GROWTH_RATE)/INCOME_PERCEPTION_ADJUSTMENT_TIME
UNITS: Euro/year/person/years

Figure 4-6 Model structure of income growth

Fuel-efficiency improvement needs investments and innovations. The model assumes that a historical improvement rate during the decades exists, due to autonomous business and household behaviour, regardless of the additional policy interventions. Figure 4-7 below shows the substructure of fuel efficiency improvements of the model. The fractional improvement rate should have a negative value because the fuel efficiency refers to the amount of fuel consumed per kilometre travelled.

Also, the model assumes that the stock, the improved fuel efficiency (liter/km), has limits to the innovation because there might be nonlinearity between the level of fuel efficiency and the rate of improvement.



Improved_Fuel_Efficiency_(liter/km)"(t) = "Improved_Fuel_Efficiency_(liter/km)"(t - dt) + (fuel_efficiency_improvement) * dt
UNITS: liter/km

fuel_efficiency_improvement = ("Improved_Fuel_Efficiency_(liter/km)"*fractional_improvement_rate)/PERIOD_OF_IMPLEMENTATION
UNITS: Liters/km/years

Figure 4-7 Model structure of the improvement in fuel efficiency

Figure 4-8 shows the CLD with major feedback loops as a summary of the dynamic hypothesis discussed so far. Against the efforts to improve fuel efficiency, two balancing loops, B1 and B2, stabilise the system, which is the critical mechanisms for arising of rebound effects. Also, two different reinforcing loops, R1 and R2, are confronting each other. The subsystem of income growth, R1, gives positive impacts on fuel consumption whereas the loop R2 of fuel efficiency improvement offers negative impacts on it. The efficiency policies increasing the efficiency improvement rate target the decoupling between fuel consumption and income growth (economic growth).

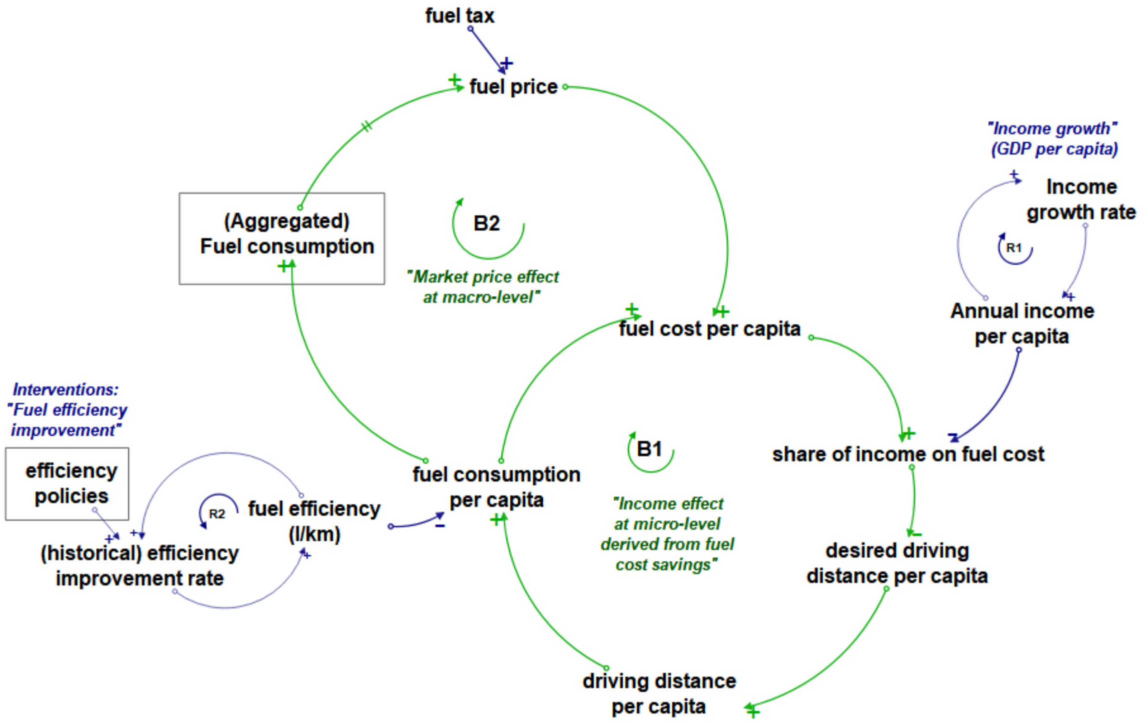


Figure 4-8 Rebound effect mechanism based on economic theory

Social practice theory enables to add more mechanisms to the above discussed dynamic hypothesis by responding differently to the question, *what causes the changes in the desired annual driving distance?* It has emphasised on the evolution of lifestyle stimulating people to buy more cars and to drive more kilometres. The expansion of infrastructures such as road networks can encourage people to use automobiles. Also, it can affect the social meaning of automobile use. By these processes, the desire to driving larger distances can be strengthened, and when this is linked to car use this will cause an increase of fuel consumption.

The dynamic hypothesis is therefore developed further by adding the perspectives of social practice theories. The model formulation was initiated from the interaction of two stocks, Road Networks and Automobile in Use. Figure 4-9 presents the SFD including the stocks and their relationships.

In Figure 4-9, the length of road networks is regulated by a balancing loop, B3, which controls the road networks in responding to the changes in road congestion. More road congestion increases the pressure to expand road networks. On the other hand, a larger size of road networks allows less road congestion. Moreover, a reinforcing loop, R3, is formed between them to facilitate the increase of road networks and the number of automobiles. More automobile use induces more road congestion, increasing the pressure to expand the road networks. Expansion of road networks intrigues more people to use the roads and to move to places further away. Eventually, people become to purchase more vehicles, increasing the number of automobiles in use on the roads. The diffusion of automobiles and road networks can also foster car-owners to travel more distances by changing the meaning of driving and car usages. These aspects may connect the subsystem of road and automobiles to the structure of cost-saving and fuel price mechanisms.

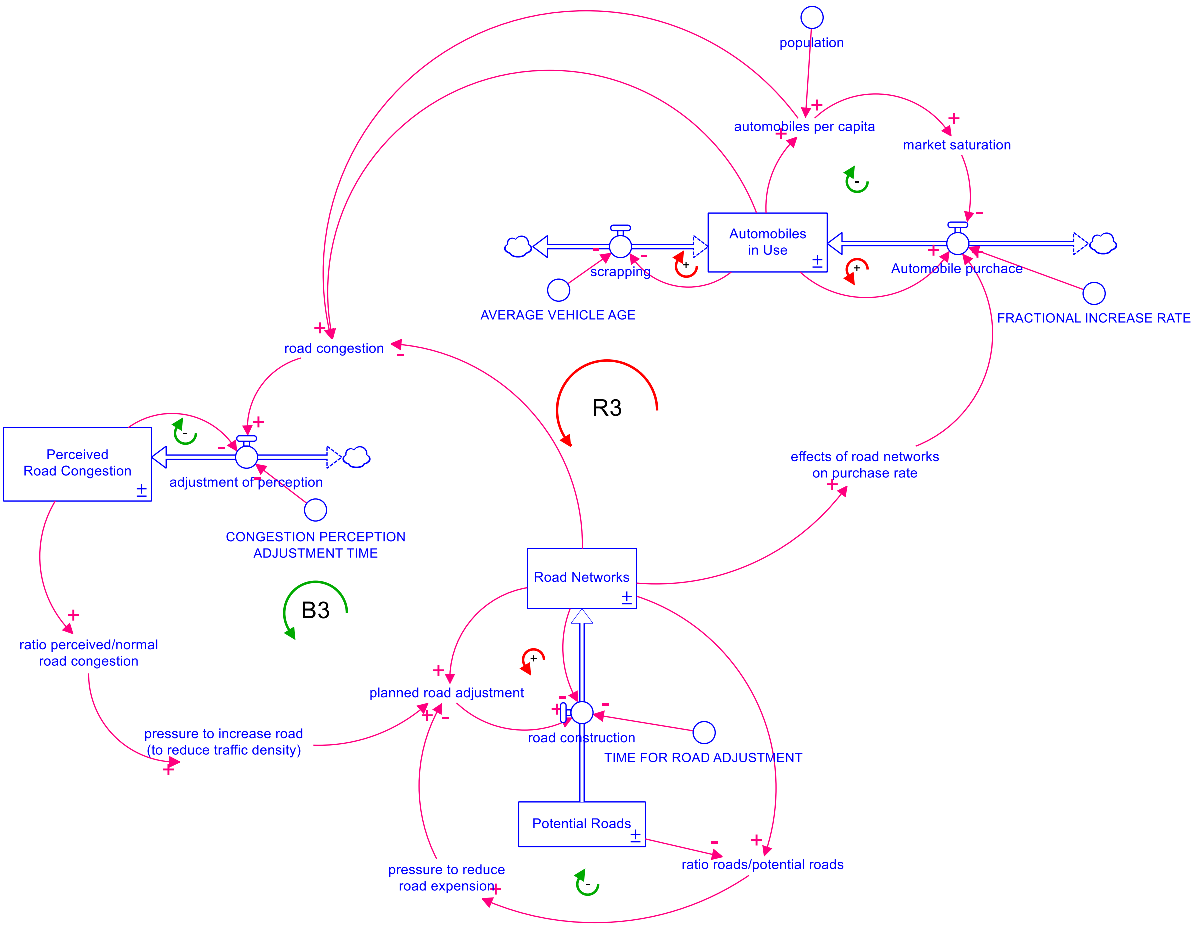


Figure 4-9 Reinforcing loop between road networks and automobiles

Figure 4-10 shows the whole model structure integrating the theoretical explanations of rebound effects from social practice theories and economic mechanisms. The main perspectives of social practice theory are on the road expansion and diffusion of automobiles. The extended road infrastructures can foster the changes in social practices related to automobile use. More road networks allow people to reach activities at a larger distance more easily. Various practices, such as shopping, commuting, and recreational activities, might each generate more car driving when their geographical locations are at larger distances from home and from each other, even when they can be combined into one door-to-door trip. The reinforcing loop, R4, shows these diffusion mechanisms of driving practices. More road networks increase the diving demand, which causes more traffic congestion, leading to the more pressure to expand the road network capacity.

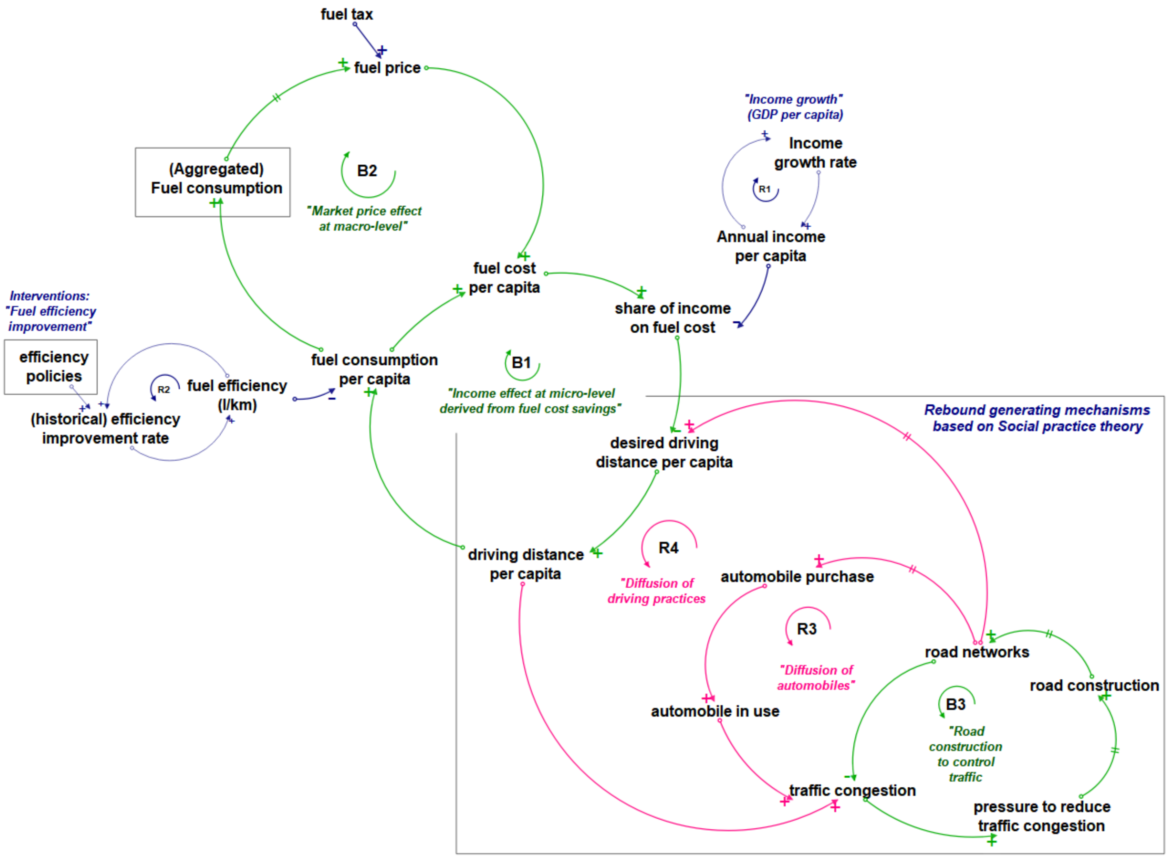


Figure 4-10 Integrated rebound effects mechanism

The conceptualised model contains a simplified structure of rebound arising mechanisms identified by the rich theoretical discussion and published research. However, it also attempts to integrate the essence of two different theories. The scope of the rebound occurrence mechanisms has consequently been significantly widened.

More importantly, the enlarged model shows the possibly arising backfires, which comes from the reinforcing loops, R3 and R4. Under the feedback loops of R1, B1, and B2, there is no possibility of backfires because the increased fuel efficiency only influences on two balancing loops with stabilising mechanisms. However, as widening the aspects of creating rebound effects to the reinforcing loops of R3 and R4, the changes in driving demand induced by efficiency improvement might be accelerated as time goes by.

4.4 Parameter estimation

The two diagrams, CLD and SFD, model the socio-economic mechanisms inducing rebound effects and allow for improving insight in these mechanisms. However, the insight should be tested through computer simulations because the mechanisms entail complex dynamic processes that are hard to be analysed by our mental simulation. The dynamic hypothesis should be tested and analysed through computer simulation to generate evidence regarding the implications of the model structures (Ford, 2010: 152).

The computer simulation requires numerical inputs for parameters. A wide range of data and information can offer sources for parameter estimation. Table 4-1 summarizes the estimated inputs with an information source for each parameter in the model. The estimation mainly depended on publicly available information, such as the official statistical database of institutes and published journal articles. However, in the case that there is no relevant data available, the estimation relied on informal data sources, such as internet websites and newspapers, to get the input values.

The values of some parameters were gained by a partial model calibration (Oliva, 2003), which includes fuel supply, fuel efficiency improvement rate, income growth rate, increase rate of automobile purchase. Since the parameters determine flows to the stocks, the adjustment with the related stock's historical trends could produce the input values. For instance, the parameter ''Historical fuel efficiency improvement rate", was deduced from an estimated trend using data on the average estimated fuel efficiency. Also, values for the "Fractional income growth rate" were gained by using the historical trends of GDP per capita.

All inputs of parameters and model equations are reported in Appendix B.

Table 4-1 Input value and source for parameters

Classification	Parameter	Value	Unit	Source
Exogenous inputs	Population	700,000,000	person	Worldometers Average population (1970-2019)
	Fuel supply (Reference supply)	88,100,000	ton/year	Estimated from the initial total fuel consumption (initial travel distance per capita*fuel efficiency*population) Assumed 10 times higher than initial total fuel consumption in 1970
	Average vehicle age	11	year	Internet source (informal data)
	Sensitivity of fuel supply to price (Supply elasticity)	0.4	unitless	Partial calibration (fuel price sector)
Initial values of stocks	Initial income per capita	7200 (8000*0.9)	Euro/year/ person	World Bank national accounts data (GDP per capita)
	Initial fuel efficiency	0.1	Liter/km	Judgement based on the Lubetsky (2011)
	Initial road network	3,400,000	km	Eurostat
	Initial driving distance	1,700	km/year/pe rson	Estimated from the transportation policy documents
	Initial automobiles in use	45,000,000	vehicle	Eurostat
	Initial fuel price	0.4	Euro/liter	European Environment Agency
	Initial annual fuel cost per capita	68	Euro/year/ person	Calculated from the initial driving distance*initial fuel efficiency*initial fuel price
Fractional change rate of flows	(historical) improvement rate of fuel efficiency	-0.01	unitless	Partial calibration (fuel efficiency improvement sector)
	Fractional income growth rate	0.035	unitless	Partial calibration (income growth sector)
	Fractional increase rate of automobile purchase	0.16	unitless	Partial calibration (number of automobile in use)

Chapter 5. Model Testing and Analysis

5.1 Model testing

The model was developed in a recursive manner, which uncovered errors and improved the model repetitively. During the model building, therefore, substantial testing was performed to increase model credibility, including the test on boundary adequacy, structure assessment, dimensional consistency, and parameter assessment. The reflective processes enhanced confidence in the model and its results.

Further model testing is required to get a more robust model. Three types of testing are reported in this chapter: Extreme condition test, Behaviour reproduction test, and Sensitivity behaviour analysis. Robust models produce the same patterns in their results, regardless of the extreme conditions and high uncertainty in parameter values (Ford, 2010: 158).

5.1.1 Extreme condition test

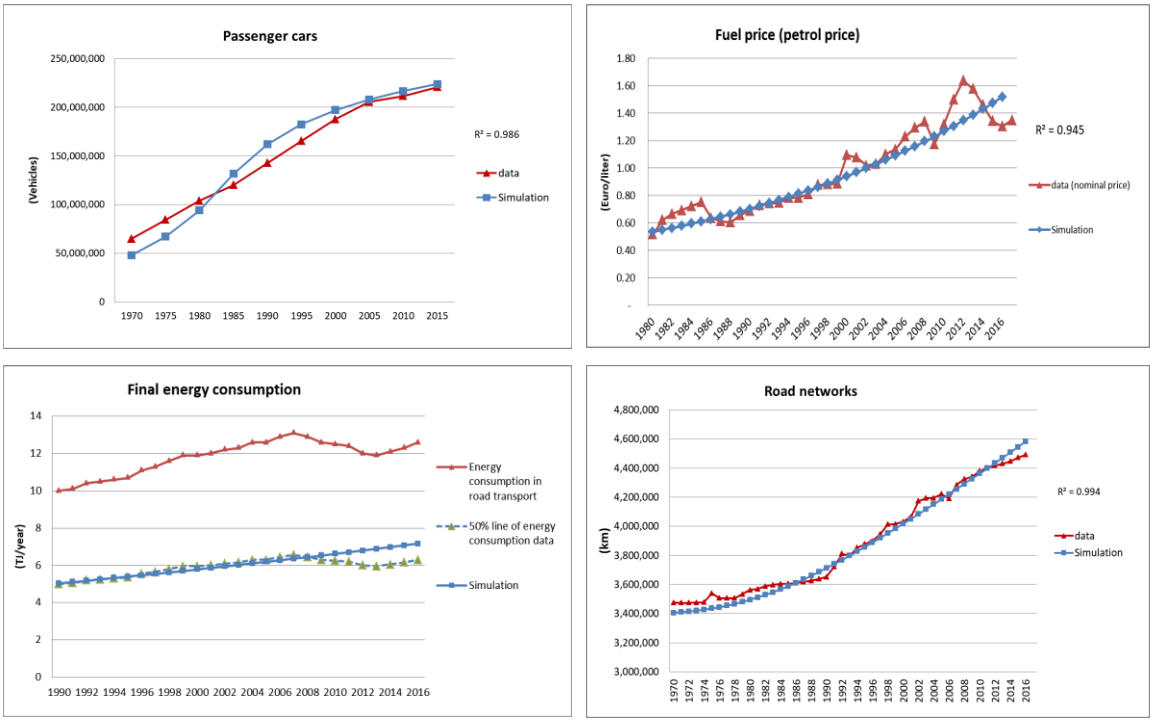
The *extreme condition test* examines each equation if it generates realistic outputs even when its inputs are unrealistic and have extreme values (Sterman, 2010: 869). The test assigned the maximum and the minimum values for the input of the rate equations and then checked the output whether it could have reasonable explanations. The current model appeared to have no critical flaws due to the testing implementation. Each rate equation in the model confirmed its robustness whether it could generate a feasible set of outputs.

5.1.2 Behaviour reproducing test

The *behaviour reproducing test* assesses whether the model can make good-fitting outputs to the data (Sterman, 2010: 874). To confirm the model's reproducibility, the simulations for the four parameters, including Fuel price, Total energy consumption, Automobile in use, and Road networks, were compared to the actual data. Figure 5-1 reports each parameter's testing results. The trend in the data is shown by the red line whereas the simulations are shown by the blue line.

Three parameters, fuel price, the number of passenger cars, and road networks, had good-fitting with data in the simulations. The coefficient of determination (r-square) for them was more than 0.9, which means the model is reproducing the behaviours of data quite well.

The data of energy consumption by the automobiles was not available. Thus, the data of the energy consumption in road transport served for the model testing. The simulation of the parameter, Total energy consumption, had good-fitting with the line of 50% of overall energy consumption in road transport. This implies the energy consumption of passenger cars roughly takes about half of the total energy use in the road transport. The others may be consumed for the road freight vehicles such as trucks, vans, and tractors. (Eurostat) It might be a little lower or higher than the reality but the behaviour pattern in the simulation was acceptable.



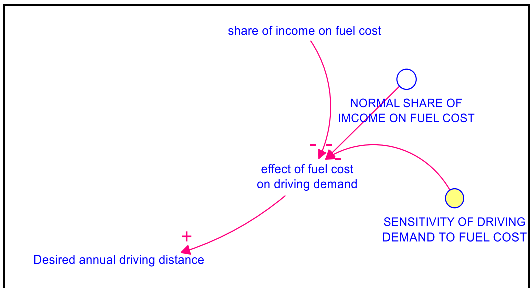
Data sources: Eurostat; European Environment Agency (2018).

Figure 5-1 Behaviour reproducing test

5.1.3 Sensitivity behaviour analysis

Sensitivity behaviour analysis examines if the model results are affected by the range of the parameter inputs (Sterman, 2010: 883). In particular with respect to uncertain parameters, it should be checked whether their inputs make any critical changes in the model results, implying that if the parameters change the general patterns in the model's outputs changes. If this is the case, the model would be sensitive to the specific parameter. In general, the test conducts multiple simulations with a full range of uncertainty in the parameters and checks if the simulations have significant variations in their results.

Seven uncertain parameters were used to conduct the sensitivity testing with five different inputs assigned within the possible range of the values. These parameters had high uncertainty because they were devised for the normalisation technique. Normalisation allows giving the effect of X variable on Y with dimensionless. The parameters named ‘sensitivity’ control the magnitude of the normalised effect by using an exponential function. For example, the parameter “effect of fuel cost on driving demand” means the normalised effect of fuel cost on driving demand. The “sensitivity of driving demand to fuel cost” becomes an exponent to the normalised effect (refers to equations in Figure 5-2 below).



effect_of_fuel_cost_on_driving_demand =
(share_of_income_on_fuel_cost/NORMAL_SHARE_OF_IMCOME_ON_FUEL_COST)^SENSITIVITY_OF_DRIVING_DEMAND_TO_FUEL_COST
UNITS: unitless

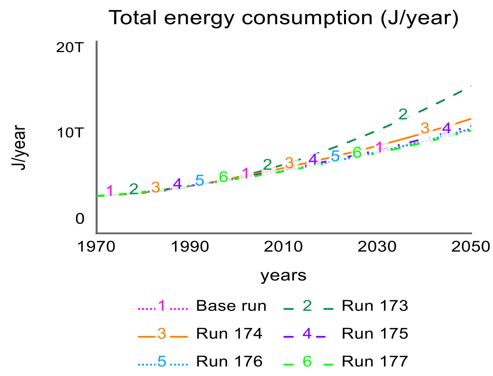
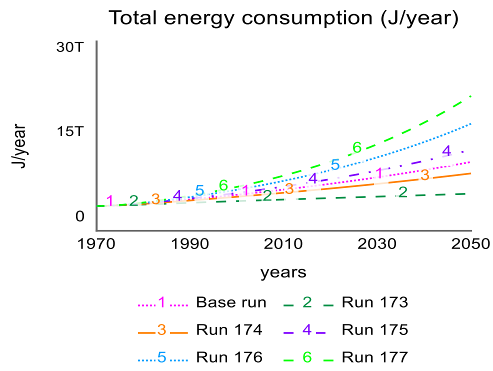
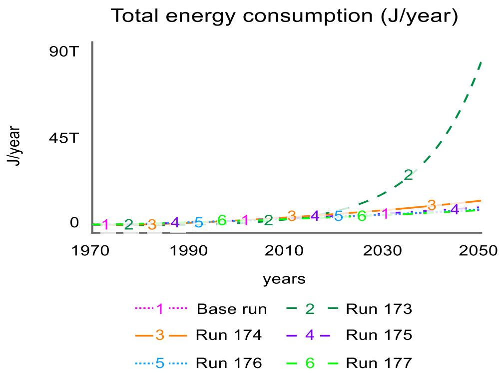
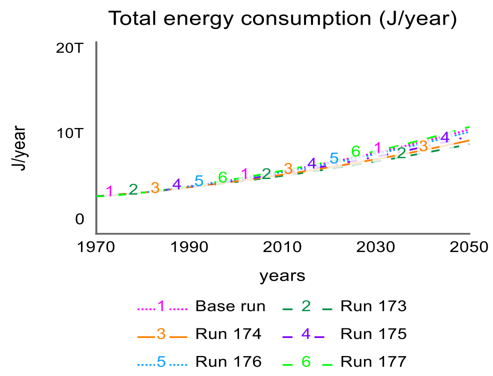
Figure 5-2 Model structure for effect normalisation

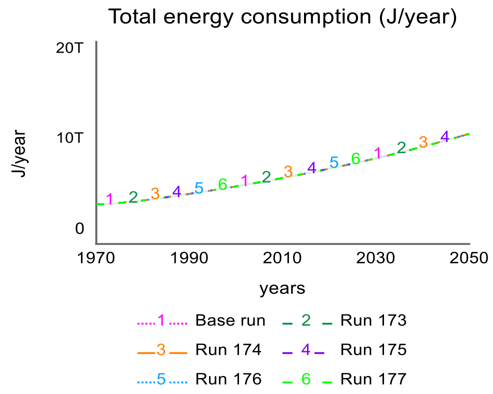
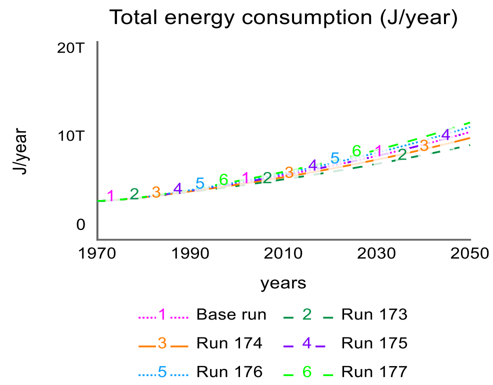
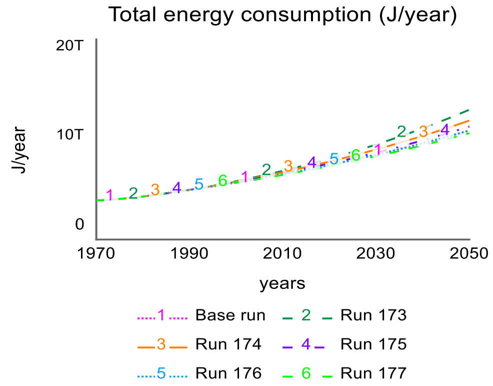
Table 5-1 illustrates the results of the sensitivity testing on the parameters in the model. Each graph shows the sensitivity of the model result to the parameters based on running multiple simulations. The base run refers to the parameter values derived from the baseline calibration. In addition to the base run, five times additional runs are presented, which refers the possible range of parameter inputs such as 0.1, 0.3, 0.5, 0.7, 0.9. The graphs of the total energy consumption (J/year) represent the model result because it defined the reference mode of the model.

Among the seven parameters, the model result reacted most sensitively to the parameter, the sensitivity of driving demand to fuel cost. Particularly the model result was sensitive to the inputs between -0.1 and -0.3 (run 173 shows the input -0.1). This implies that if the effect of fuel cost on the driving demand downwards enough, the energy consumption will significantly increase. Despite the highest sensitivity of the parameter, it did not harm the general pattern of the model result.

The model was also relatively sensitive to the parameter “sensitivity of fuel supply to price”. The testing outcome showed that more flexibility in the fuel supply to the changes in fuel price could lead to more energy consumption. For example, the input 0.1 and 0.3 (run 173 and 174) presents less change in the trend of energy consumption whereas the input 0.7 and 0.9 (run 176 and 177) have relatively large variation in the increase of energy consumption.

Table 5-1 Sensitivity analysis results

Parameters	Input of Base run (model input)	Possible range of the parameters (inputs of sensitivity analysis)	Sensitivity of total energy consumption to the parameters
Sensitivity of price to demand/supply balance	0.7	0< value <1 (0.1, 0.3, 0.5, 0.7, 0.9)	
Sensitivity of fuel supply to price	0.4	0< value <1 (0.1, 0.3, 0.5, 0.7, 0.9)	
Sensitivity of driving demand to fuel cost	-0.8	-1< value <0 (-0.1, -0.3, -0.5, -0.7, -0.9)	
Sensitivity of driving demand to road networks	0.8	0< value <1 (0.1, 0.3, 0.5, 0.7, 0.9)	

Parameters	Input of Base run (model input)	Possible range of the parameters (inputs of sensitivity analysis)	Sensitivity of total energy consumption to the parameters
Sensitivity of car purchase to road networks	0.5	0< value <1 (0.1, 0.3, 0.5, 0.7, 0.9)	
Sensitivity of road adjustment to traffic density	0.5	0< value <1 (0.1, 0.3, 0.5, 0.7, 0.9)	
Sensitivity of road adjustment to road saturation	-0.7	-1< value <0 (-0.1, -0.3, -0.5, -0.7, -0.9)	

5.2 Model Analysis

5.2.1 Energy consumption under improved fuel efficiency

After calibration and testing, the model was used to run a baseline simulation under the current historical trends. The model was calibrated with the data from 1970 to 2017 and then the simulation expanded the time horizon until 2050. Figure 5-3 shows the simulation results. Among the three lines in the graph, the first line shows the baseline developments of energy consumption. Under the current trends, fuel efficiency would be improved by up to 22.3% during 2010-2050. Energy consumption shows a trend of a continuously increasing level until 2050.

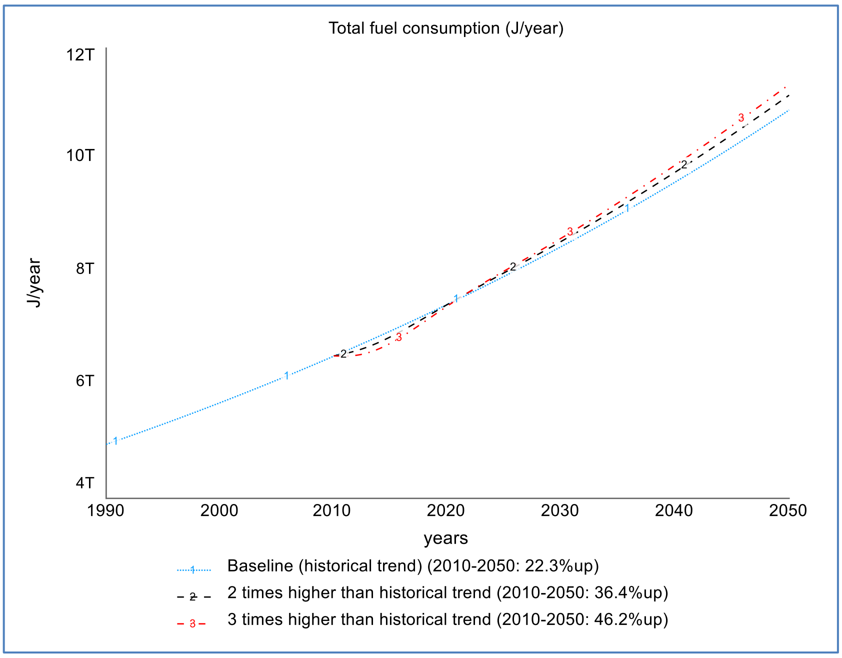


Figure 5-3 Long-term developments in energy consumption under the different fuel efficiencies

In addition to the baseline, multiple simulations for 2010-2050 are presented in Figure 5-3. They allow exploring the futures of the energy consumption developments, assuming different improvement scenarios of fuel efficiency. The second line of the graph indicates the situation that we have two times higher improvement rate in fuel efficiency than the historical trends, which means we will have 36.4% improvements in fuel efficiency during 2010-2050. Also, the third line shows the case that we have three times higher rates of the improvements, which means 46.2% increase during 2010-2050.

The result showed that the improvements in fuel efficiency could only have energy savings in the short-term, approximately until the year 2020 in this simulation. In the long-term, however, according to the simulations rebound effects will arise and eventually backfires will occur. Paradoxically, the higher the level of fuel efficiency is, the more energy will be consumed, which is a counter-intuitive conclusion.

In addition, the graph reveals that the level of fuel efficiency is not giving a significant impact on the developments of the overall energy consumption. Figure 5-4 below presents both simulation results of two parameters: the graphs of fuel efficiency and of total energy consumption. All three cases in the graph of the energy consumption have the same behavioural patterns, expressing a continuously increasing level over time (see the graph in the right part of Figure 5-4), although different levels of fuel efficiency are assumed (see the graph in the left part of Figure 5-4). Also, this result does not match general expectations.

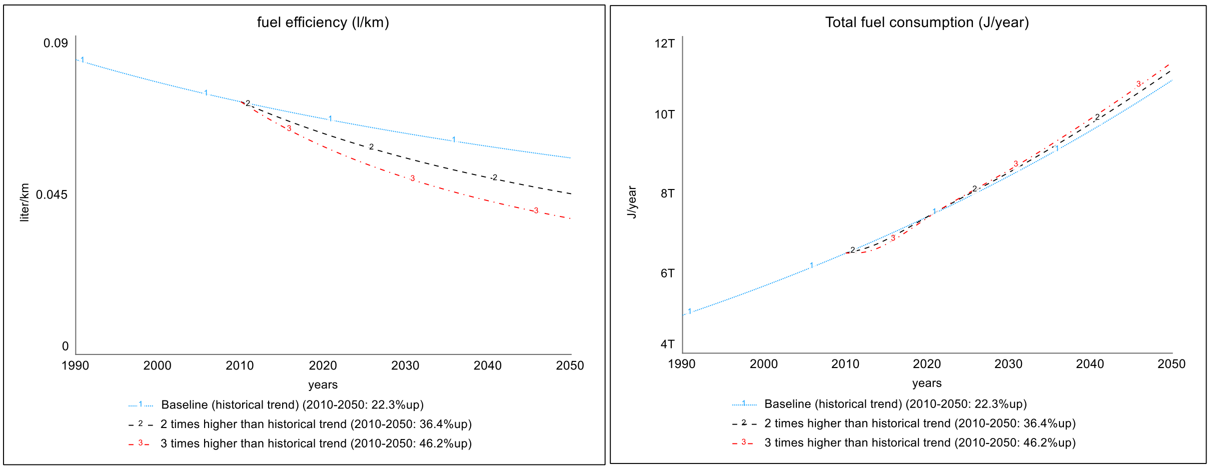


Figure 5-4 Simulation results of fuel efficiency and energy consumption

5.2.2 Understanding of model results

The computer simulations produced problematic behaviours in the energy consumption developments. These can be considered as the reference mode in the study. Even though fuel efficiency is assumed to be improved, it appears hard to find the expected, sufficiently large, savings and reductions in energy consumption. Rather, in spite of the improvements in fuel efficiency, the energy consumption keeps steadily increasing and it seems to increase even more rapidly than before, which strongly suggests backfire effects. The simulations also reveal that fuel efficiency does not have any critical effects on the energy consumption developments, which significantly weakens the (expectations on the) effectiveness of the energy efficiency policies in terms of energy security and climate change mitigation.

In order to learn on the problem, we need to understand the results from the perspective of the underlying model structures and simulations. Figure 5-5 summarizes the model structure and Figure 5-6 contains the simulation results for the parameters in the model. These provide the basis for interpreting the parameters' behaviours, leading to a concrete understanding of rebound generating mechanisms.

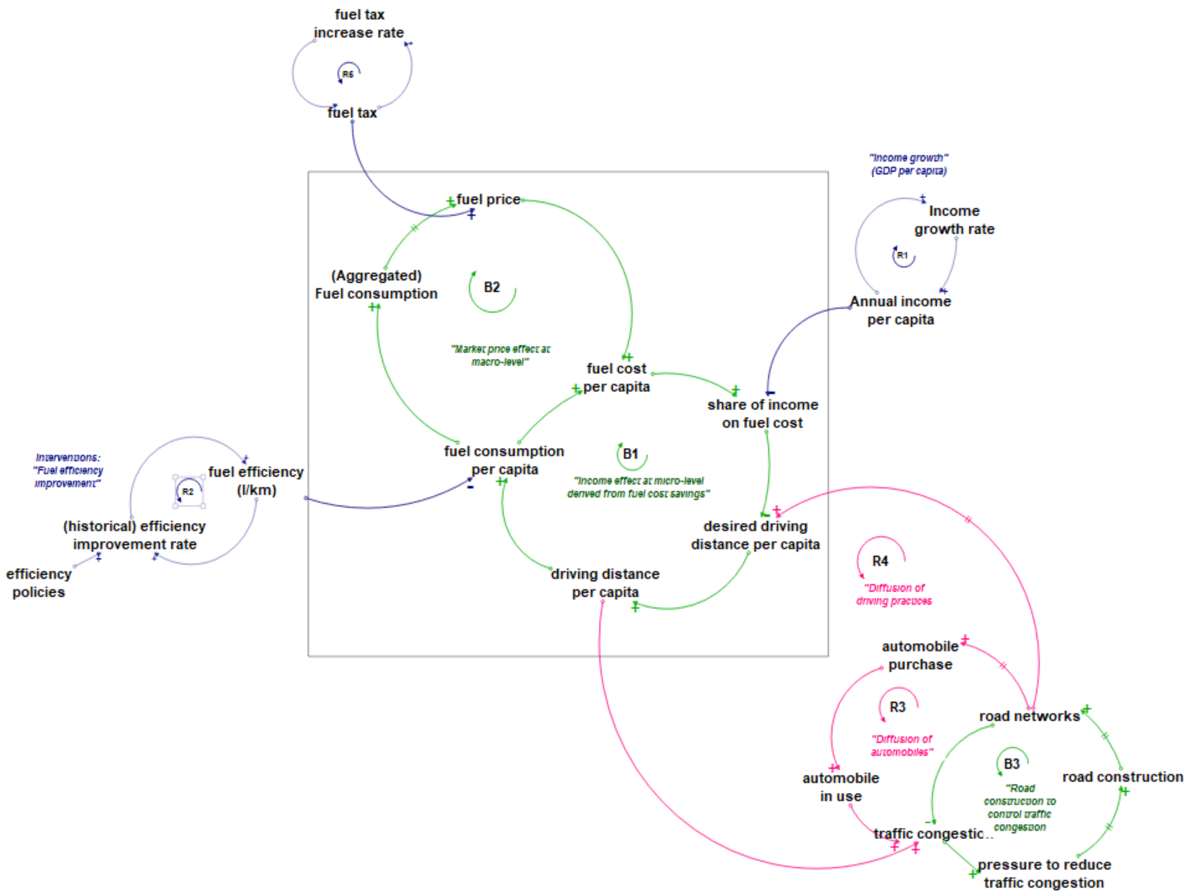


Figure 5-5 Model structure

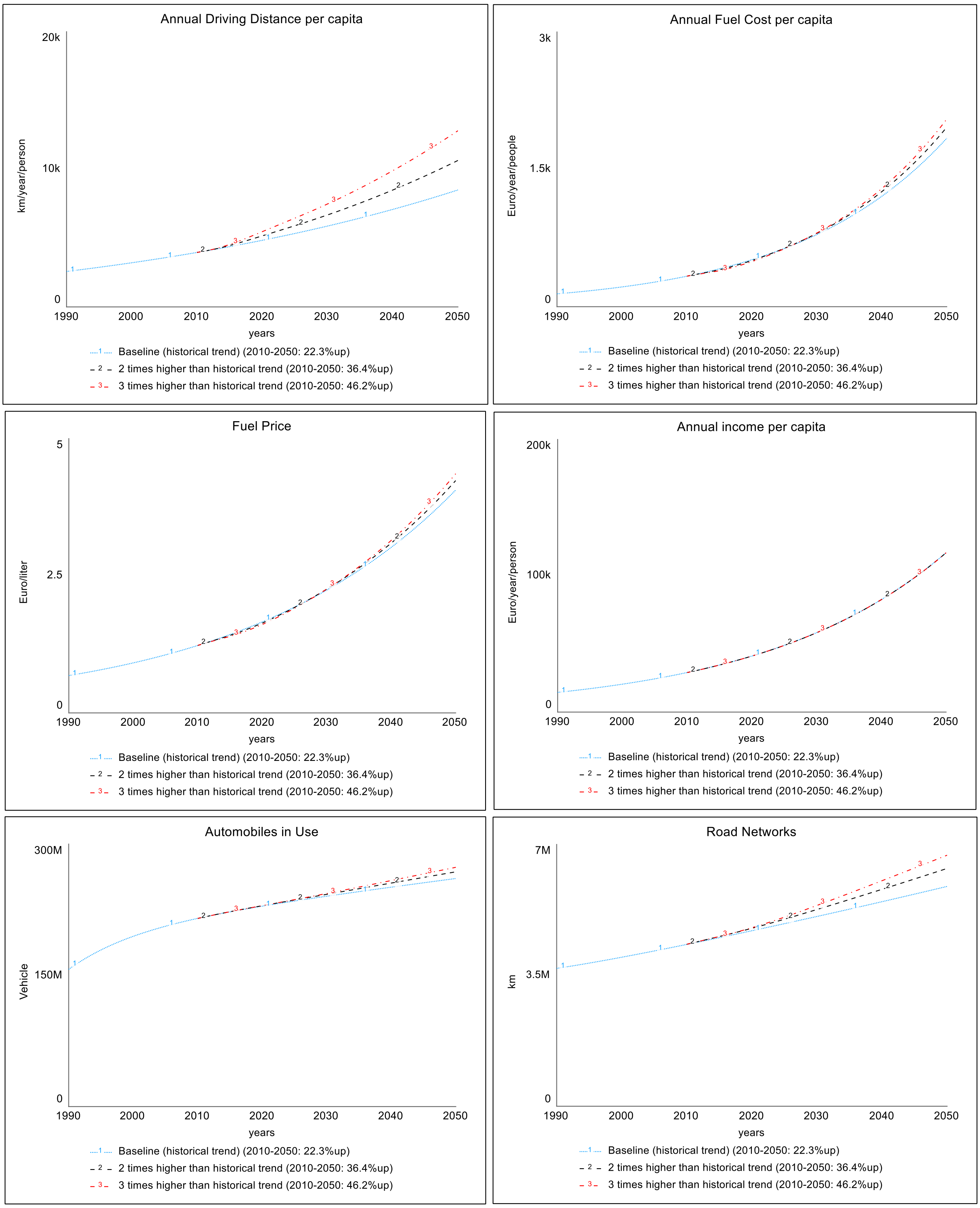


Figure 5-6 Simulation results of major parameters

In the simulations, rebound effects are directly induced by the increasing driving distance per capita. The simulations of driving distance per capita clearly show that higher fuel efficiency allows for travelling at larger distances, offsetting possible energy savings. It is necessary to decompose the underlying structures to increase driving distances in order to have a clearer understanding of the rebound generating mechanisms.

In the model structure, the driving distance per capita is firstly regulated by a balancing loop, B1. In the balancing loop, the stock variable is adjusted to seek the desired status, generating a goal-seeking behaviour. The share of income on fuel costs serves for a goal in this feedback loop. In other words, the system operates in such a way that the fuel costs per capita stays at a certain portion of income (in the model, the initial portion was set as 0.01. If the share in income becomes larger, the desired driving distance will decrease; and reversely: if the portion is smaller, the driving distance will increase), which was the primary mechanism generating rebound effects. When the improved fuel efficiency reduces fuel cost per capita, and income remains at the same level, the system resists the change by recovering fuel cost through increasing the driving distance. Consequently, a growing income will generate more distances driven, which will be even stronger in combination with fuel efficiency improvements.

Another balancing loop, B2, was included as an additional mechanism for controlling driving distance per capita. In this feedback structure, the fuel price acts as a central variable. Following the causal loop, increased fuel efficiency lowers the aggregated fuel demand, leading to a cheaper price in the market. The price adjustment enables to reduce the fuel cost per capita, which increases the driving distance again and therefore causes a recovering of fuel demand. This has also been presented as an explanation of why rebound effects occur.

According to the balancing mechanisms, B1 and B2, the driving distance per capita and energy consumption should be stabilised over time. Also, fuel price was expected to generate stability. However, the simulations showed the steadily increasing levels of these variables. These trends are basically derived from the growing income per capita. The changes in incomes are driven by a reinforcing loop, R1, which causes an exponentially increase over time.[4]

The income growth mechanism, R1, serves as an exogenous input to the balancing loops B1 and B2. Increasing income supports the growth of driving distances and fuel consumption by reducing the portion of income on fuel cost. It also enables the endless increase in fuel price. Higher income allow for spending more money on fuel consumption, which increases fuel demand in the market,

[4] The underlying structure of income growth can be controversial. A reinforcing loop might not reflect the diverse views to the income growth such as the argument for the limit to growth, or overshooting and collapse. However, this study simply followed the view of the limitless growth because most reports to forecast energy consumption trends published by the EU took this point of view. For example: Capros et al. (2016). *EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050.*

resulting in higher fuel prices. Despite the inflation of price, more budget-spending on fuel consumption is, in this causal mechanism, possible due to a steady income growth.

A confrontation between the two reinforcing loops, R1 for income growth and R2 for fuel-efficiency improvement, can be observed. Each reinforcing loop influences the balancing loops, B1 and B2, in the opposite direction. The income growth contributes to increasing the desired driving distance, resulting in an increase in energy consumption, whereas fuel-efficiency improvement aims to decrease it.

The conflicting structures imply that the changing rates of incomes and fuel efficiency can be the crucial parameters to regulate energy consumption. A faster speed of income growth, compared to the speed of fuel-efficiency improvement, appears to be a sufficient condition to offset the expected energy reductions from the improved fuel efficiency. It means that the improvement in fuel efficiency is hardly able to reduce energy consumption in a societal system that is also characterized by a fast growth of its economy, presuming that this growth also results in steady income growth of households. Rather, it can be an effective way of enjoying more travel-kilometres per unit fuel consumption. The energy reductions caused by the efficiency improvement would be recovered to the original consumption level in the long run because there appears to be, on average, always sufficient income to cope with increased fuel costs and to stimulate driving longer distances.

Under the consideration of these structural mechanisms, fuel tax may be a solution to tackle the increasing energy consumption. It can act as another exogenous input to the balancing mechanisms, B1 and B2. Fuel tax will directly increase the fuel price, regardless of income growth. It increases fuel cost per capita and gives negative impacts on the increase of car-driving. Both fuel tax and fuel-efficiency improvement influence the balancing loops, B1 and B2 in the same direction, reducing energy consumption, against the income growth mechanism.

If we see only these structures, B1, B2, R1, and R2, there is theoretically no possibility for backfires to appear. The maximum rebound effect is theoretically expected to be 100%. This is because there is no underlying causal structure to induce a higher level of driving demand than before the improvement in fuel efficiency, apart from income growth.[5] However, the simulations did show backfires in the long-term developments of energy consumption. The main explanation for this is the relationship between driving demand and road network extension.

So, the reinforcing loops R3 and R4 are the critical structures to induce backfires. The R3 serves for the underlying mechanism to increase automobile-in-use and road networks over time. The increasing number of automobiles causes increasing road congestion, and this at its turn leads to the

[5] If someone thinks there might be a causal relationship between the fuel-efficiency improvement and income growth, the possibility of backfire would exist. However, this is out of the boundary of the model.

expansion of road networks. The expanded road capacity causes an increase in the purchase of automobiles. Also, another reinforcing loop, R4, is relevant for the relationship between driving demand and road networks. Where R3 stresses more car-driving causing an increase in road congestion, which leads to expansion of road networks, R4 stresses the mechanism that the expansion of road networks affects lifestyles to become more automobile dependent, and thus increases car-driving for longer distances.

The influence of the reinforcing loops, R3 and R4, on the balancing loops, B1 and B2, are endogenous. The adjustment of the road network is dependent on the state of driving distance per capita. At the same time, the driving demand is adjusted by the level of road expansion. The mutual adjustment can produce a path dependency of the system in which small events in early time frames of the system can be amplified over time and determine the system’s ultimate destination. Also, it means that the system has floating goals, which implies that the desired state of the system is not constant. It also changes according to the changes in the state of the system (Sterman, 2010: 533). These amplifying mechanisms under the reinforcing loops, R3 and R4, produce backfire effects.

The rebound effect, increasing driving distances, were initiated from the B1 and B2 loops, in the early period of time, but the driving demand was amplified by the reinforcing mechanisms as time continues. In this structure, the level of driving demand and the expansion of road network capacity depends on the adjustment time of each state of the system. Faster adjustments allow more amplification of the changes, which increases the magnitude of backfires. The model structure suggests a possible option to mitigate backfires. That is, if the reaction of road expansion to the road congestion can delay long enough, the amplification of the system’s changes would be slow down, which might be a solution to escape from the backfire effect.

5.2.3 Simulation experiments

The simulations and model structures gave insight into the relationships between fuel-efficiency improvements and energy consumption. The increase of fuel efficiency enables to drive more distances per unit amount of fuel, which creates more utilities and human welfare. However, it does not ensure a reduction in energy consumption. Rather, it is likely that it causes significant rebound effects leading to less than the expected reduction of energy consumption, or even backfires leading to an increase in energy consumption.

Policy experiments were conducted to explore the potential impact of some policy options to mitigate rebound effects. The simulations examined each option's long term impacts on energy consumption as well as driving distance which refers to the enjoyable utility in the experiment. They elucidated possible pathways to decouple between energy consumption and driving distance as well as to overcome backfires.

Four variables were selected for the simulation experiments: Fuel-efficiency improvement rate, Fuel tax increase rate, Income growth rate, and Sensitivity of road adjustment to traffic density. The changing rates of fuel efficiency, fuel tax, and income determine the magnitude of exogenous inputs for the regulating mechanisms of energy consumption and driving distance (B1 and B2). Faster changes in the rates allow more variations on the values of each input for fuel efficiency, fuel tax, and income per capita. Next, the sensitivity of road adjustment to traffic density decides how fast the road construction responds to the road congestion, which is critical for the speed of amplification of the system changes through the positive feedback loops (R3 and R4).

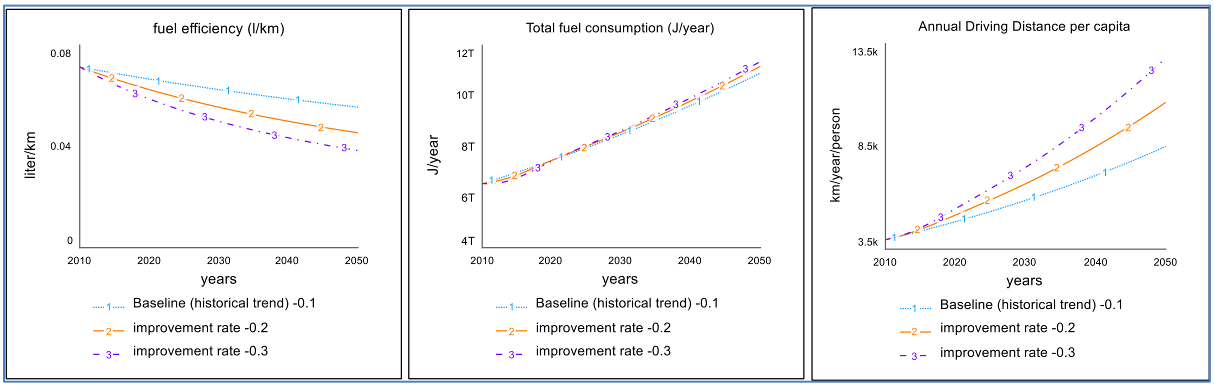
The simulation experiments consist of four tests of each single-policy option, as listed in Table 5-2. Experiment 1 serves for the reference experiment because it tests the fuel-efficiency policy under the historical trends, which were analysed in the previous section. Experiment 2 tests the fuel tax policy. The simulation uses a range of fuel tax rates. In addition to the baseline input 0.01, higher fuel tax rate, 0.05 and 0.07, are also simulated to see the outcome of the increased tax imposition. Experiment 3 assesses the policy option of slowing the growth of the economy. Apart from the historical growth rate of 0.035, the lower rates, 0.025 and 0.015, are also tested to see the outcome of the decreasing economic growth. Experiment 4 investigates the policy option of slowing the adjustment of road networks. The baseline used the input of 0.5. In addition, input values of 0.3 and 0.1 were also simulated. The experiment can show the result of a slow response of road expansion to road congestion.

Table 5-2 Single-policy experiments

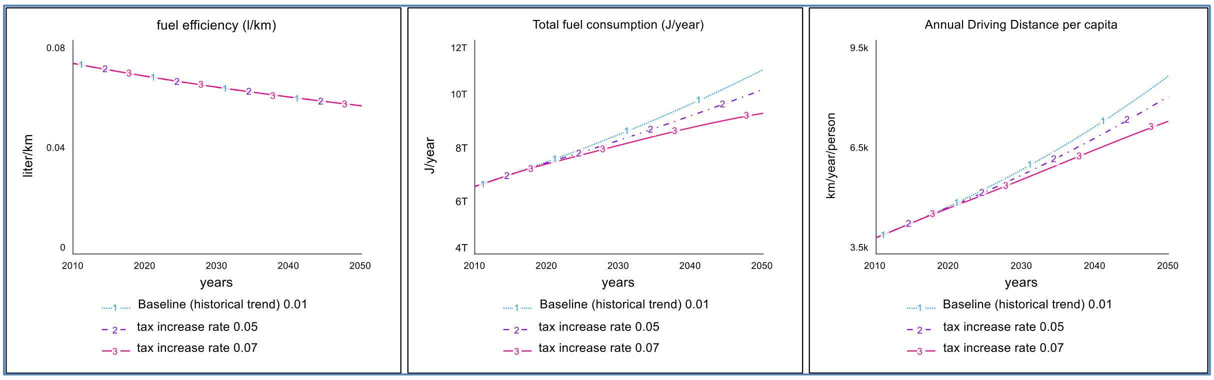
Simulation experiment	Policy options	Model inputs				Meaning
		Fuel-efficiency improvement rate	Fuel tax increase rate	Income growth rate	Sensitivity of road adjustment to traffic density	
Experiment 1 (Reference)	**Fuel efficiency**	-0.1 -0.2 -0.3	0.01	0.035	0.5	Fuel efficiency improvements under the baseline condition (without changes in fuel tax increase rate, income growth rate, and road adjustment)
Experiment 2	**Fuel tax**	-0.1	0.01 0.05 0.07	0.035	0.5	Instead of fuel-efficiency improvement, opt the increase fuel tax imposition (No changes in fuel-efficiency improvement rate, income growth rate, and road adjustment)
Experiment 3	**Slow economic growth**	-0.1	0.01	0.035 0.025 0.015	0.5	Instead of fuel-efficiency improvement, opt the slow-down in income growth rate (No changes in fuel-efficiency improvement rate, tax increase rate, and road adjustment)
Experiment 4	**Slow adjustment of road networks**	-0.1	0.01	0.035	0.5 0.3 0.1	Instead of fuel-efficiency improvement, opt the slowing the adjustment of road networks (No changes in fuel-efficiency improvement rate, tax increase rate, and income growth rate)

Figure 5-7 displays the simulation results of each policy option comparing them in terms of energy consumption and driving distances. The results clearly show that the fuel-efficiency policy allows more driving-kilometres than the baseline development. However, it does not produce energy savings and reductions.

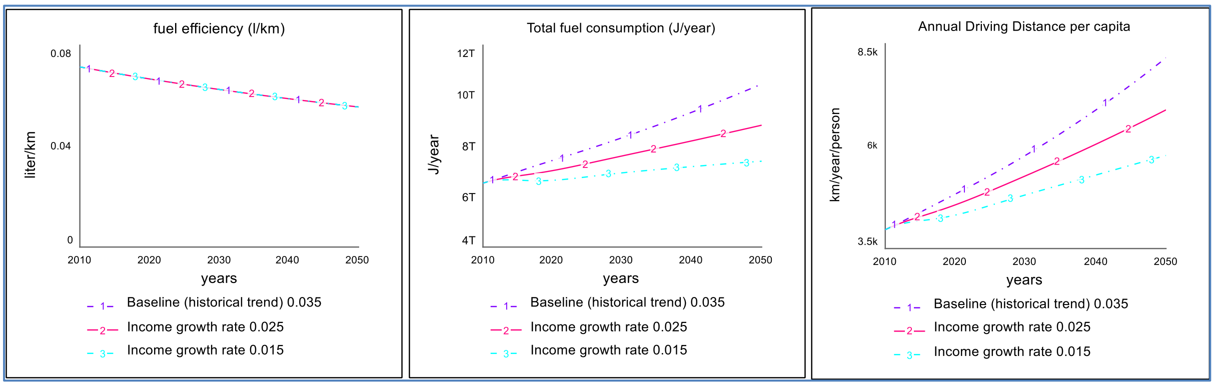
Experiment 1 (Reference) – Fuel efficiency



Experiment 2 – Fuel tax



Experiment 3 – Slowing economic growth



Experiment 4 – Slowing adjustment of road networks

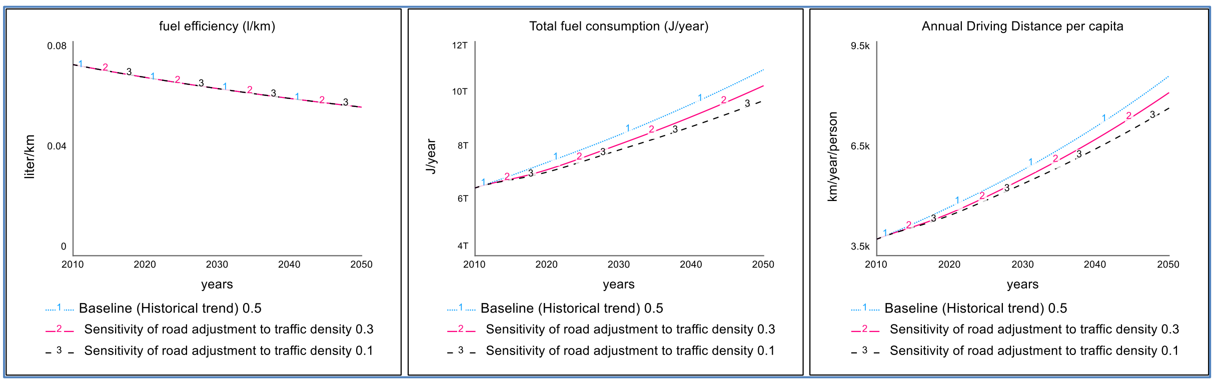


Figure 5-7 Simulations of single-policy option experiments

The option of a raising fuel tax, on the other hand, could be more effective for saving energy than the efficiency policies. The results suggest that a faster increase in fuel tax ensures a more significant energy reduction. The energy reductions were the results of reducing driving distances as compared to the baseline. It failed to decouple between energy consumption and driving distance, which might not be the most desirable outcome from a societal point of view.

The slowdown in economic growth shows a similar pattern in the simulation results as the variation in fuel tax. The results suggest that income decrease seems the most powerful option to tackle energy consumption. However, also in this case the energy savings are achieved only by decreasing driving distances. It could not decouple energy consumption from useful activities.

Slowing the adjustment of road network also follows the same pattern as the other policy options in the simulations. Although the slow reaction to the road congestion seems less powerful than fuel tax and the slowdown in economic growth, it is definitely more effective to reduce energy consumption than the efficiency improvements. Nevertheless, it also could not accomplish the decoupling between energy consumption and driving distance because it reduces the driving distance and energy consumption at the same time.

The simulation experiments for the four single-policy options suggest the following policy implications: Fuel-efficiency policies can be beneficial to enjoy more utilities, but it fails to save energy, which implies it also less effective to mitigate climate change. The alternative policy options, including fuel tax, slowing the income-growth, and slowing the road expansion, commonly appear in a more powerful way than the efficiency improvements to decrease energy consumption. However, they also fail to decouple the energy consumption from the amount of useful activities.

The simulations show that only relying on a single-policy option is hard to decouple energy consumption from the driving distance, which might be the most desirable outcome of the policy options. Therefore, further investigations focused on combining policy options to investigate their combined effects. Another seven experiments were implemented, as shown in Table 5-3. The model inputs of each experiment were designed to simulate the combined effects between fuel-efficiency policies and fuel tax, or/and reduced income growth, or/and slowing road expansion.

The experiments of the combined-policies add policy options step by step. Experiment 5, 6, 7, tests the combination of two policy options which combines the fuel efficiency policy with alternative policies, fuel tax, slow economic growth, and slowing adjustment of road networks. Experiment 8, 9, 10, tests further the combined-policy options in which the fuel efficiency policy mixes with the selected two more policy options among three. Finally, Experiment 11 assesses the combination of four policy options altogether.

Table 5-3 Combined-policy experiments

Simulation experiment	Policy options	Model inputs				Meaning
		Fuel-efficiency improve ment rate	Fuel tax increase rate	Income growth rate	Sensitivity of road adjustment to traffic density	
Experiment 5	Fuel efficiency + Fuel tax	-0.1 -0.2 -0.3	0.07	0.035	0.5	Fuel-efficiency improvement with high fuel-tax rate and under the current income growth rate
Experiment 6	Fuel efficiency + Slow economic growth	-0.1 -0.2 -0.3	0.01	0.015	0.5	Fuel-efficiency improvement under the slow income growth circumstances without a fuel-tax increase
Experiment 7	Fuel efficiency + Slow adjustment of road networks	-0.1 -0.2 -0.3	0.01	0.035	0.1	Fuel-efficiency improvement under the slow road expansion without a fuel-tax increase
Experiment 8	Fuel efficiency + Fuel tax + Slow economic growth	-0.1 -0.2 -0.3	0.07	0.015	0.5	Fuel-efficiency improvement with high fuel-tax rate and slow income growth circumstances
Experiment 9	Fuel efficiency + Fuel tax + Slow adjustment or road networks	-0.1 -0.2 -0.3	0.07	0.035	0.1	Fuel-efficiency improvement with high fuel-tax rate and slow road expansion
Experiment 10	Fuel efficiency + Slow economic growth + Slow adjustment or road networks	-0.1 -0.2 -0.3	0.01	0.015	0.1	Fuel-efficiency improvement with slow income growth and road expansion
Experiment 11	Fuel efficiency + Fuel tax + Slow economic growth + Slow adjustment or road networks	-0.1 -0.2 -0.3	0.07	0.015	0.1	Fuel-efficiency improvement with high fuel-tax rate, slow income growth, and slow road expansion

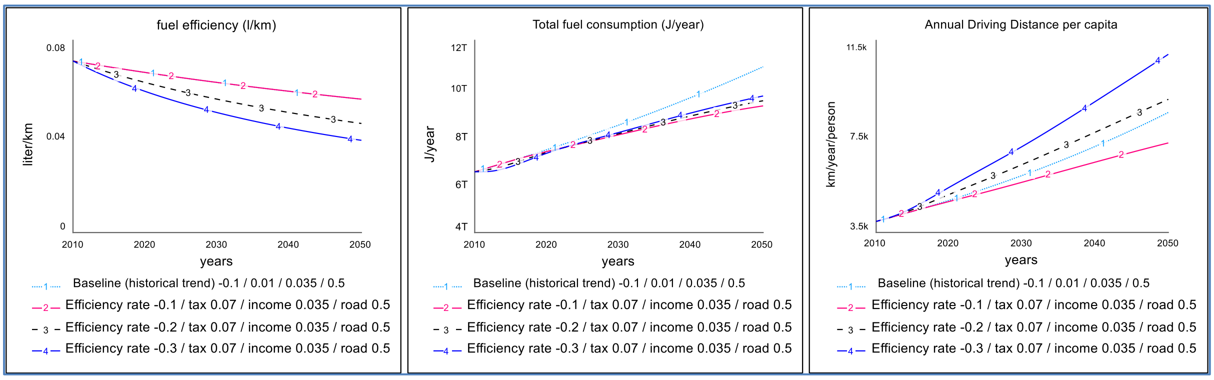
Figure 5-8 presents the simulation results of combined-policy experiments. All results of the combined-policies commonly show a reduced level of energy consumption compared to the baseline that solely improves energy efficiency. The backfire effect disappeared in the graphs. These results imply that rebound effects from the improved fuel efficiency generally can be mitigated when the efficiency policies are implemented in combination with higher fuel tax imposition or/and the circumstance of lowering economic growth or/and less responds to road congestion.

The results of experiments 5, 6, 7, and 9, show a possibility of the decoupling between energy consumption and driving distance. In the graphs of the results, the level of driving-kilometres increase but the energy consumption decrease, compared to the baseline projection. This means that it would be possible to decouple energy consumption from the driving distance if the fuel-efficiency policies were implemented in combination with a higher fuel tax or with a lower rate of economic growth or a strategy of slowing down adjustment of road networks. Those may become a better policy option than the fuel-efficiency policy alone because they suggest that significant rebound effects can be avoided and that decoupling is within reach.

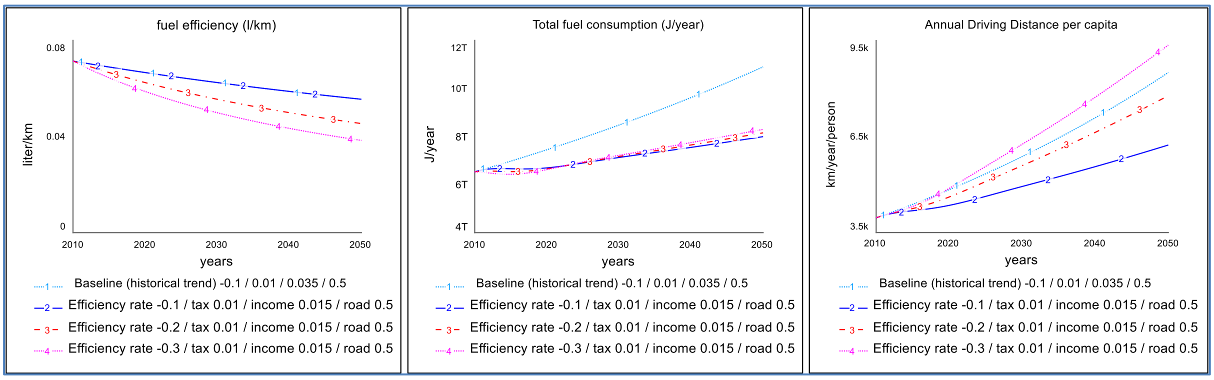
Among the combined-policy options, both fuel tax and a slower road expansion policy produces similar policy outcomes. The combination of fuel efficiency with fuel tax or slower adjustment of road networks has relatively smaller energy savings but is more beneficial to car-driving than the case of the combination with slowing down the growth of the economy. On the other hand, the policy option of slowing down the growth of the economy can result in relatively larger energy savings but it cannot avoid the decreases in driving-distances.

When the efficiency policy is mixed with both rising the fuel tax and a lower economy growth, the energy consumption becomes stabilised and finally decreases in the long term (see the results of the experiments 8 and 11 in Figure 5-8). The combination might offer a possible pathway to tackle the current increasing trend in energy consumption, as well as the challenges of energy depletion and climate change. However, the driving distances have to be stabilised and reduced compared to baseline in these cases.

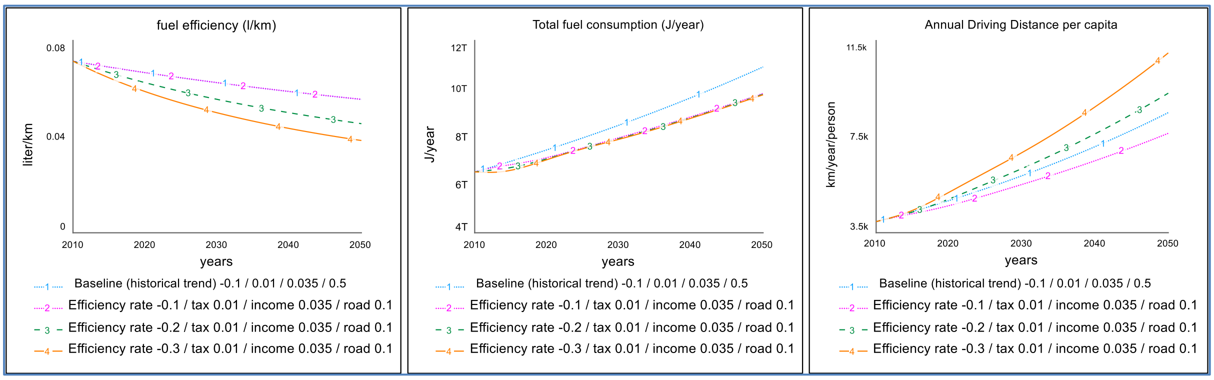
Experiment 5 – Fuel efficiency + Fuel tax



Experiment 6 – Fuel efficiency + Slowing economic growth



Experiment 7 – Fuel efficiency + Slowing adjustment of road networks



Experiment 8 - Fuel efficiency + Fuel tax + Slowing economic growth

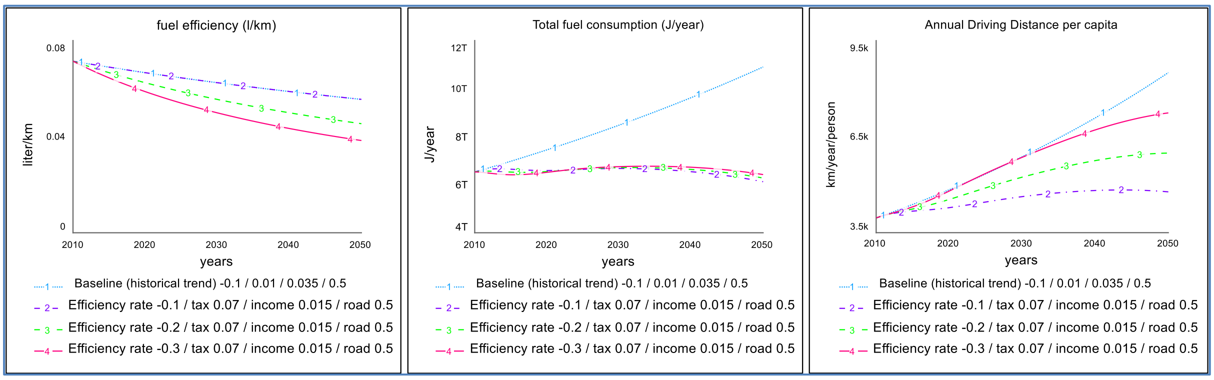
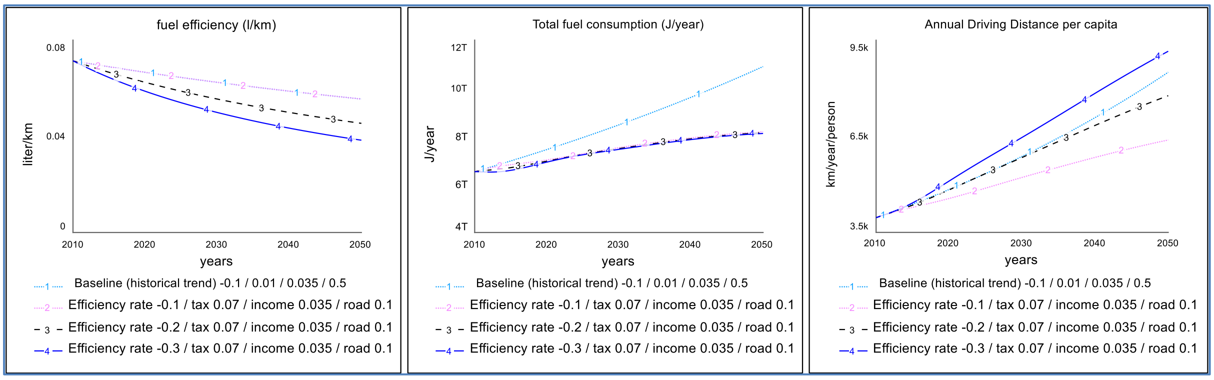
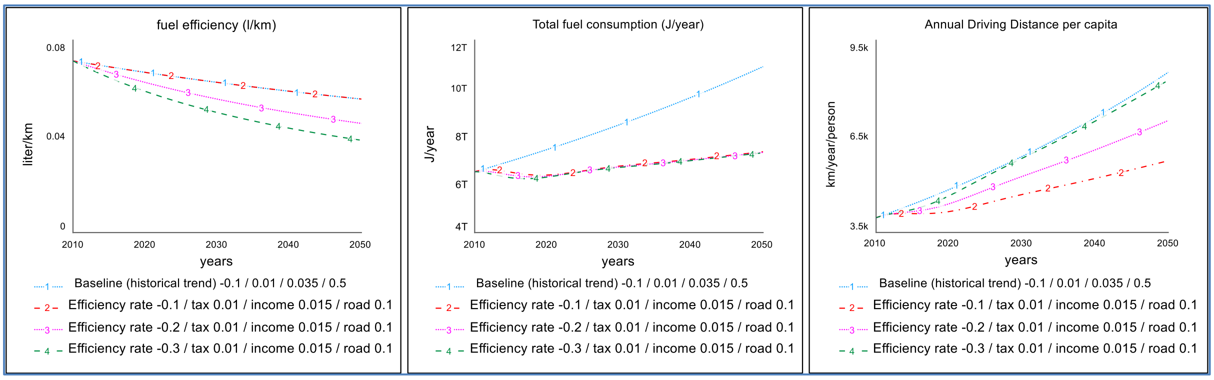


Figure 5-8 Simulations of combined-policy experiments

Experiment 9 - Fuel efficiency + Fuel tax + Slowing adjustment of road networks



Experiment 10 - Fuel efficiency + Slowing economic growth + Slowing adjustment of road networks



Experiment 11 - Fuel efficiency + Fuel tax + Slowing economic growth + Slowing adjustment of road networks

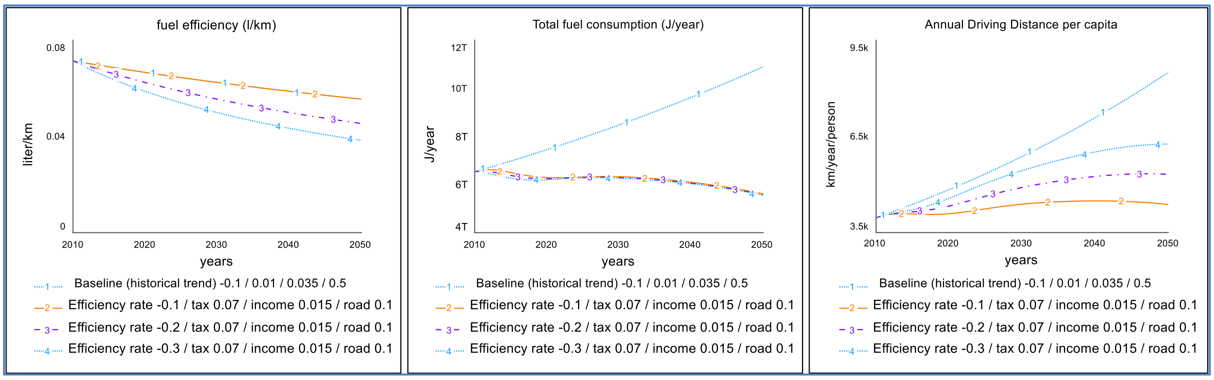


Figure 5-8 Simulations of combined-policy experiments (continued)

Chapter 6. Conclusion

6.1 Findings and insight

The study investigated the rebound effects, the underlying causal mechanisms, and impacts on the future trend of energy consumption, from the improvements in energy efficiency, in the transport sector. System dynamics modelling converged two different branches of theory explaining the rebound mechanisms - economic theory and social practice theory. Both theories offer explanations for the dynamic processes that cause the occurrence of rebound effects, even though they have some contradictory point of views in their theoretical grounds and assumptions. System dynamics modelling enables to encompass both economic and societal processes generating rebound effects.

Computer simulations allowed seeing the long-term effect of the enhancement in energy efficiency, compared to the baseline trend, showing the size of the contribution to the energy saving goals. Multiple simulations on the automobile fuel-efficiency indicated that the increase of fuel-efficiency would not be as effective as expected to save energy since it causes more car-driving per unit amount of energy consumed. In the early period of implementing efficiency policies, energy consumption slightly decreases. However, in later periods, significant rebound effects occur that offset the energy savings in the previous years. Even backfires effects appeared in the simulations: under certain conditions the amount of car-driven kilometres moves significantly upwards due to efficiency improvement, resulting in consuming more energy than before.

The model structures uncovered why the significant rebound effects and backfires emerge in the long run. Energy consumption and the activities to use energy are regulated by balancing loops, which seek to stay at an equilibrium state. Important is the exogenous level of the energy efficiency improvement. This has direct influence, via the feedback structures, on the move towards equilibrium. The corrective actions in the system react to the change in the input, moving the system back to the original equilibrium. This is the systematic reason why the rebound effects are triggered. However, the magnitude of the reaction may not be substantial in case of a strong enforcement of efficiency policies, which can change the input radically.

The main reason for the observed substantial rebound effects is derived from the developments in another exogenous input: growing income. The efficiency policies appear to directly compete with income growth with regard to the system performance on energy use. Faster growing in incomes hinders efficiency policies to have significant energy savings influence. Under these mechanisms, full rebound effects are strongly likely to happen because the saved costs of energy use due to improved energy efficiency policies, will in the end be used to develop more activities, often also at larger distances.

Furthermore, the model structures revealed the systematic mechanisms of backfires. These appear mainly driven by the societal processes that the social practice theory puts emphasis on, such as changing infrastructures, changing norms on wellbeing, and changing lifestyle. The social structures and the system of energy use are mutually dependent. The rebound behaviours in the system of energy use, also triggers changes in social structures, which at its turn again has impacts on the energy consuming behaviours. These interactions reinforce one another. The reinforcing feedback loops tend to amplify relatively small changes to the larger impacts on the system performance.

The study conducted scenario simulations to discover the potential value of alternative policy options. Four policy options and their combined long-term effects were examined by simulation experiment: Energy efficiency policy, Tax imposition on energy price, the Slowdown of economic growth, and the Slow expansion of road networks. The systematic exploration of rebound effects aimed to give insight in whether variation in the efficiency improvement rate, variation in the income growth rate, variation in the level of tax imposition on energy prices, and variation in the sensitivity of adjustment of road networks to road congestion, can be considered as options for mitigating rebound effects.

The simulation results showed that the energy efficiency policy could be effective to increase energy productivity and to create more enjoyable activities per unit energy. However, it would fail to save energy. On the other hand, the increasing tax on energy price or the slower growth of the economy or the slower expansion of road networks revealed to be more effective to reduce energy consumption. If the efficiency policies were mixed with other policy options that can decrease energy consumption, it appears possible to decouple the trends between energy consumption and being able to perform valuable activities. In case the policy priority is put on the issues of energy security and climate change, then slowing down the growth of the economy would be the most powerful way to move downward in the level of energy consumption. Moreover, the combination of the efficiency policy with fuel tax and a slower expansion of road networks can stabilise and decrease energy consumption in the long term. Current policies aimed at merely increasing energy efficiency are, giving these findings, significantly less effective and powerful.

6.2 Limitations

The study has clear limitations regarding the generalisability of the model and the simulation results to the overall energy sector.

First, it only dealt with automotive fuel efficiency and transport-related behavioural mechanisms, to investigate the rebound effects. Future research should investigate other sectors of energy efficiency, such as in the domain of building, consumer production, and the service industry (e.g. logistics), to obtain a more general conclusion.

Secondly, the model only formulated direct rebound effects. Indirect and more comprehensive effects were not included in the model in order to limit its complexity and to keep the required data collection manageable. Further extension of the model would be required to deal with indirect rebound effect.

Thirdly, the model draws a boundary excluding developments regarding alternative fuels and electric cars. Also, it excluded the dynamics of energy supply and the possibility of the connection between energy efficiency and economic growth. These boundaries limit the focus of the model to the study of the underlying causal relationship between the future of the increased energy efficiency and the occurrence of rebound effects. Including the in this study excluded developments will possibly shed a different light on the energy saving trends in the transport sector.

Fourthly, there were various uncertainties regarding the values of some parameters, such as the historical fuel efficiency improvement rate, the income growth rate, the fuel supply, the fuel supply elasticity, the increase rate of fuel-tax, the automobile purchase rate, the sensitivity of desired driving distance on road networks, and so on. They were estimated by data collection from different sources and partial model calibration and tested by sensitivity analyses. Further sophisticated estimations and additional information on these parameters are required to enhance the model credibility.

Finally, the model structures were developed based on the theoretical explanations from economic theory and social practice theory. The theoretical discussion has given plenty of details but the model had to be simple. Although the model had recursive tests on its structures to build confidence, it might still have structural limitations. To more systematically explore these should be subject of future study.

References

Barlas, Y. (2007). System dynamics: Systemic feedback modeling for policy analysis. *System*, *1*(59). 1-29.

Berkhout, P. H., Muskens, J. C., & Velthuijsen, J. W. (2000). Defining the rebound effect. *Energy policy*, *28*(6-7), 425-432.

Binswanger, M. (2001). Technological progress and sustainable development: what about the rebound effect?. *Ecological economics*, *36*(1), 119-132.

Capros, P. et al. (2016). *EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050*. European Commission, Directorate-General for Energy, Directorate-General for Climate Action, and Directorate-General for Mobility and Transport.

Chakravarty, D., Dasgupta, S., & Roy, J. (2013). Rebound effect: how much to worry?. *Current opinion in environmental sustainability*, *5*(2), 216-228.

Dimitropoulos, J. (2007). Energy productivity improvements and the rebound effect: An overview of the state of knowledge. *Energy Policy*, *35*(12), 6354-6363.

Duranton, G. & Turner, M. A. (2011). The fundamental law of road congestion: Evidence from US cities. *American Economic Review*, *101*(6), 2616-52.

Ehrhardt-Martinez, K. & Laitner, J. A. (2010). Rebound, technology and people: mitigating the rebound effect with energy-resource management and people-centered initiatives. In *ACEEE summer study on energy efficiency in buildings,* 7-76.

European Commission (2001). *White Paper European transport policy for 2010: time to decide*. Office for Official Publications of the European Communities, Luxembourg.

European Environment Agency (2017). *Monitoring CO2 emissions from new passenger cars and vans in 2016*. European Environment Agency (EEA) report No.19/2017.

European Environment Agency (2018). Final energy consumption by mode of transport. November 2018. Indicator assessment. IND-133-en. Available from: https://www.eea.europa.eu/data-and-maps/indicators/transport-final-energy-consumption-by-mode/assessment-9#tab-related-briefings

European Parliament (2015). Understanding energy efficiency. European Parliamentary Research Service, Briefing October 2015.

Eurostat database: https://ec.europa.eu/eurostat/data/database

Fawcett, T., Rosenow, J., & Bertoldi, P. (2019). Energy efficiency obligation schemes: their future in the EU. *Energy Efficiency*, *12*(1), 57-71.

Ford, A. (2010). *Modelling the environment*. 2nd Edition. Island Press.

Freeman, R., Yearworth, M., & Preist, C. (2016). Revisiting Jevons' paradox with system dynamics: Systemic causes and potential cures. *Journal of Industrial Ecology*, *20*(2), 341-353.

Gillingham, K., Rapson, D., & Wagner, G. (2016). The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy*, *10*(1), 68-88.

Größler, A. & Milling, P. (2007). Inductive and deductive system dynamics modeling. Paper presented at the The 2007 International Conference of the System Dynamics Society. July 29–August 2 2007. Boston, MA Available from: http://systemdynamics.org/conferences/2007/proceed/index.htm

Haas, R. & Biermayr, P. (2000). The rebound effect for space heating Empirical evidence from Austria. *Energy policy*, *28*(6-7), 403-410.

Herring, H. & Roy, R. (2007). Technological innovation, energy efficient design and the rebound effect. *Technovation*, *27*(4), 194-203.

Herring, H. & Sorrell, S. (Eds.). (2009). Energy efficiency and sustainable consumption. *The Rebound Effect.* Palgrave Macmillan UK, Hampshire.

IEA (2018). *World energy outlook 2018*. International Energy Agency (IEA).

Irrek, W. (2011). How to reduce the rebound effect?. In *International Economics of Resource Efficiency*, 279-285. Physica-Verlag HD.

Jenkins, J., Nordhaus, T., & Shellenberger, M. (2011). *Energy emergence: rebound and backfire as emergent phenomena*. The Breakthrough Institute.

Kennedy, E. H., Cohen, M. J., & Krogman, N. T. (2015). Social practice theories and research on sustainable consumption. *Putting Sustainability into Practice: Applications and Advances in Research on Sustainable Consumption*, 3-22.

Labanca, N. & Bertoldi, P. (2018). Beyond energy efficiency and individual behaviours: policy insights from social practice theories. *Energy policy*, *115*, 494-502.

Lubetsky, J. (2011). History of Fuel Economy. *Pew Environment Group*.

Madlener, R. & Alcott, B. (2009). Energy rebound and economic growth: A review of the main issues and research needs. *Energy*, *34*(3), 370-376.

Madlener, R. & Turner, K. (2016). After 35 years of rebound research in economics: where do we stand?. In *Rethinking Climate and Energy Policies* (pp. 17-36). Springer, Cham.

Mattioli, G., Anable, J., & Vrotsou, K. (2016). Car dependent practices: Findings from a sequence pattern mining study of UK time use data. *Transportation Research Part A: Policy and Practice*, *89*, 56-72.

Maxwell, D., Owen, P., McAndrew, L., Muehmel, K., & Neubauer, A. (2011). *Addressing the rebound effect*. A report for the European Commission DG Environment, 26.

Michaels, R. J. (2012). *Energy efficiency and climate policy: The rebound dilemma*. Institute for Energy Research.

ODYSSEE (2016). Energy efficiency trends in transport in EU countries. Policy brief December 2016. http://www.odyssee-mure.eu/publications/policy-brief/transport-efficiency-trends-policy-brief.pdf

ODYSSEE (2017). Overall trends in energy efficiency in the EU. Policy brief February 2017. Available from: http://www.odyssee-mure.eu/publications/policy-brief/overall-energy-efficiency-trends.pdf

Oliva, R. (2003). Model calibration as a testing strategy for system dynamics models. *European Journal of Operational Research*, *151*(3), 552-568.

Peters, A. & Dütschke, E. (2016). Exploring rebound effects from a psychological perspective. In *Rethinking Climate and Energy Policies* (pp. 89-105). Springer, Cham.

Polimeni, J. M., Mayumi, K., Giampietro, M., and Alcott, B. (2008). *The Jevons Paradox and the Myth of Resource Efficiency Improvements*. Earthscan, London & Sterling, VA.

Reckwitz, A. (2002). Toward a theory of social practices: A development in culturalist theorizing. *European journal of social theory*, *5*(2), 243-263.

Rosa, H. (2013). *Social acceleration: A new theory of modernity*. Columbia University Press.

Santarius, T. (2016a). Investigating meso-economic rebound effects: production-side effects and feedback loops between the micro and macro level. *Journal of cleaner production*, *134*, 406-413.

Santarius, T. (2016b). Energy efficiency and social acceleration: macro-level rebounds from a sociological perspective. In *Rethinking Climate and Energy Policies* (pp. 143-160). Springer, Cham.

Santarius, T., Walnum, H. J., & Aall, C. (2016). Introduction: Rebound Research in a Warming World. In *Rethinking Climate and Energy Policies* (pp. 1-14). Springer, Cham.

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ü rge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy implications. *Annual Review of Environment and Resources*, *41*, 425-452.

Shove, E. (2003). Converging conventions of comfort, cleanliness and convenience. *Journal of Consumer policy*, *26*(4), 395-418.

Shove, E. (2017). Energy and social practice: from abstractions to dynamic processes. In *Complex Systems and Social Practices in Energy Transitions* (pp. 207-220). Springer, Cham.

Shove, E., Trentmann, F., & Wilk, R. (Eds.). (2009). *Time, consumption and everyday life: practice, materiality and culture*. Berg.

Shove, E., Watson, M., & Spurling, N. (2015). Conceptualizing connections: Energy demand, infrastructures and social practices. *European Journal of Social Theory*, *18*(3), 274-287.

Small, K. A. & Van Dender, K. (2007). Fuel efficiency and motor vehicle travel: the declining rebound effect. *Energy Journal*, *28*(1), 25-51.

Sonnberger, M., & Gross, M. (2018). Rebound effects in practice: An invitation to consider rebound from a practice theory perspective. *Ecological economics*, *154*, 14-21.

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. (2009). Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy policy*, *37*(4), 1456-1469.

Stapleton, L., Sorrell, S., & Schwanen, T. (2016). Estimating direct rebound effects for personal automotive travel in Great Britain. *Energy Economics*, *54*, 313-325.

Sterman, J. (2010). *Business dynamics*. McGraw-Hill.

Sterner, T. & Coria, J. (2013). *Policy instruments for environmental and natural resource management*. Routledge.

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy policy*, *30*(4), 317-325.

Van den Bergh, J. C. (2011). Energy conservation more effective with rebound policy. *Environmental and resource economics*, *48*(1), 43-58.

Vivanco, D. F., Kemp, R., & Van der Voet, E. (2016). How to deal with the rebound effect? A policy-oriented approach. *Energy Policy*, *94*, 114-125.

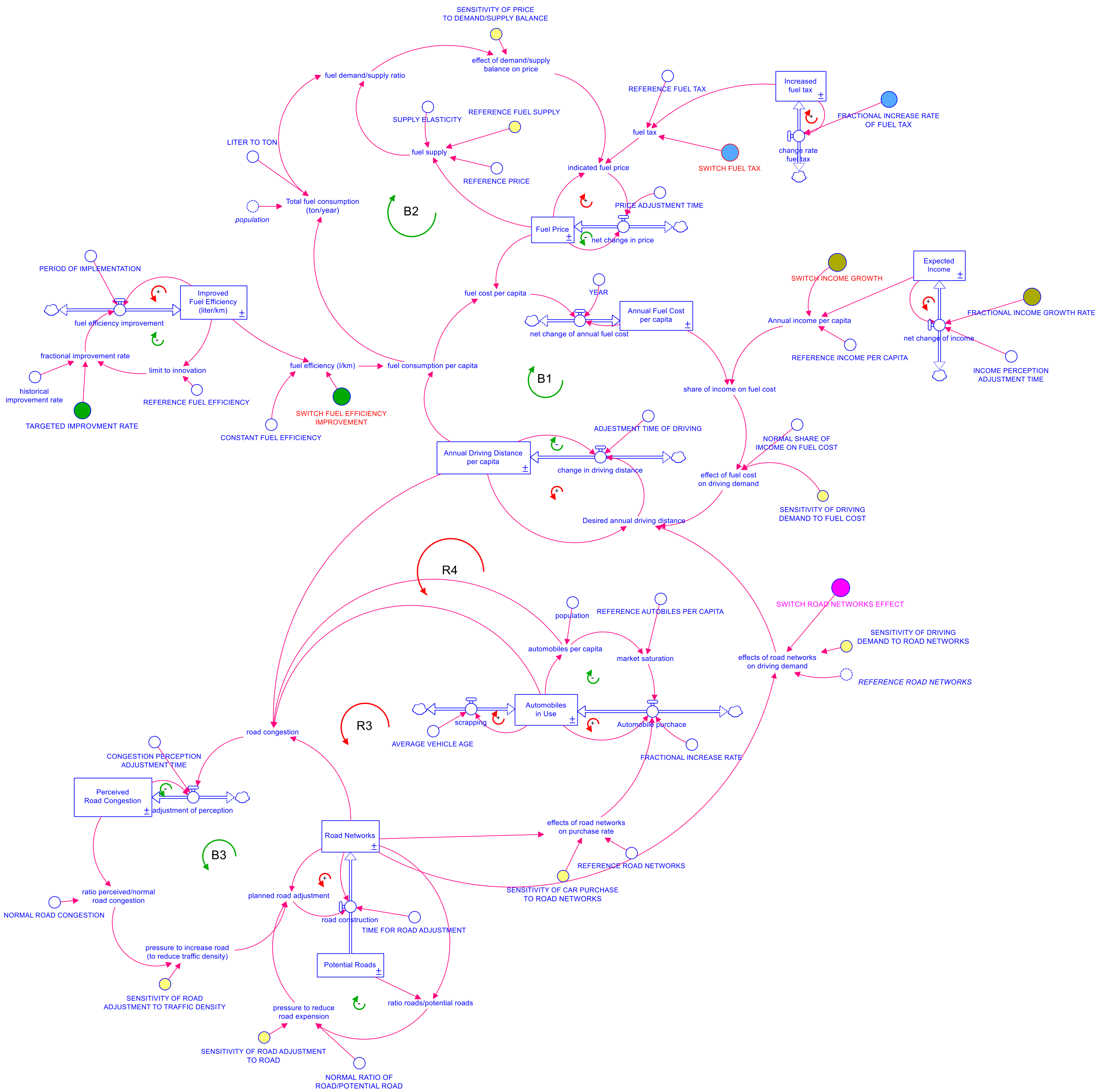
Walker, G., Shove, E., & Brown, S. (2014). How does air conditioning become 'needed'? A case study of routes, rationales and dynamics. *Energy Research & Social Science*, *4*, 1-9.

Wallenborn, G. (2018). Rebounds are structural effects of infrastructures and markets. *Frontiers in energy research*, *6*, 99.

Warde, A. (2005). Consumption and theories of practice. *Journal of consumer culture*, *5*(2), 131-153.

Worldometers: www.Worldometers.info

Appendix A – Model structure



Appendix B – Model equations

{ INITIALIZATION EQUATIONS }

: S Annual_Driving_Distance_per_capita = 1700

UNITS: km/year/person

: S Annual_Fuel_Cost_per_capita = 68

UNITS: Euro/year/people

: S Automobiles_in_Use = 45000000

UNITS: Vehicle

: c REFERENCE_INCOME_PER_CAPITA = 8000*0.9

UNITS: euro/year/person

: S Expected_Income = REFERENCE_INCOME_PER_CAPITA

UNITS: Euro/year/person

: S Fuel_Price = 0.4

UNITS: Euro/liter

: S "Improved_Fuel_Efficiency_(liter/km)" = 0.1

UNITS: liter/km

: S Increased_fuel_tax = 0.04

UNITS: euro/liter

: c NORMAL_ROAD_CONGESTION = 350000

UNITS: km/km/year

: S Perceived_Road_Congestion = NORMAL_ROAD_CONGESTION

UNITS: 1/year

: S Potential_Roads = 3500000*10

UNITS: km

: S Road_Networks = 3400000

UNITS: km

: c CONGESTION_PERCEPTION_ADJUSTMENT_TIME = 3

UNITS: year

: c population = 700000000

UNITS: person

: c automobiles_per_capita = Automobiles_in_Use/population

UNITS: vehicle/person

: c road_congestion =
((Annual_Driving_Distance_per_capita/automobiles_per_capita)*Automobiles_in_Use)/Road_Networks

UNITS: km/km/year

: f adjustment_of_perception = (road_congestion-
Perceived_Road_Congestion)/CONGESTION_PERCEPTION_ADJUSTMENT_TIME

UNITS: 1/year/years

: c FRACTIONAL_INCREASE_RATE = 0.16

UNITS: unitless

: c REFERENCE_ROAD_NETWORKS = 3500000

UNITS: km

: c SENSITIVITY_OF_CAR_PURCHASE_TO_ROAD_NETWORKS = 0.5

UNITS: unitless

: c effects_of_road_networks_on_purchase_rate =
(Road_Networks/REFERENCE_ROAD_NETWORKS)^SENSITIVITY_OF_CAR_PURCHASE_TO_ROAD_NETWORKS

UNITS: unitless

: c REFERENCE_AUTOBILES_PER_CAPITA = 0.17

UNITS: Vehicle/person

: c market_saturation = MAX(automobiles_per_capita/REFERENCE_AUTOBILES_PER_CAPITA, 1)

UNITS: unitless

: c YEAR = 1

UNITS: Years

: f Automobile_purchace =
Automobiles_in_Use*(FRACTIONAL_INCREASE_RATE*effects_of_road_networks_on_purchase_rate/market_saturation)/YEAR

UNITS: Vehicle/years

: c SWITCH_INCOME_GROWTH = 1

UNITS: unitless

: c Annual_income_per_capita = REFERENCE_INCOME_PER_CAPITA*(1-SWITCH_INCOME_GROWTH)+Expected_Income*SWITCH_INCOME_GROWTH

UNITS: Euro/year/person

: c share_of_income_on_fuel_cost = Annual_Fuel_Cost_per_capita/Annual_income_per_capita

UNITS: unitless

: c NORMAL_SHARE_OF_IMCOME_ON_FUEL_COST = 0.01

UNITS: unitless

: c SENSITIVITY_OF_DRIVING_DEMAND_TO_FUEL_COST = -0.8

UNITS: unitless

: c effect_of_fuel_cost_on_driving_demand = (share_of_income_on_fuel_cost/NORMAL_SHARE_OF_IMCOME_ON_FUEL_COST)^SENSITIVITY_OF_DRIVING_DEMAND_TO_FUEL_COST

UNITS: unitless

: c SENSITIVITY_OF_DRIVING_DEMAND_TO_ROAD_NETWORKS = 0.8

UNITS: unitless

: c SWITCH_ROAD_NETWORKS_EFFECT = 1

UNITS: unitless

: c effects_of_road_networks_on_driving_demand = SWITCH_ROAD_NETWORKS_EFFECT*((Road_Networks/REFERENCE_ROAD_NETWORKS)^SENSITIVITY_OF_DRIVING_DEMAND_TO_ROAD_NETWORKS)+(1-SWITCH_ROAD_NETWORKS_EFFECT)

UNITS: unitless

: c Desired_annual_driving_distance = Annual_Driving_Distance_per_capita*effect_of_fuel_cost_on_driving_demand*effects_of_road_networks_on_driving_demand

UNITS: km/year/person

: c ADJESTMENT_TIME_OF_DRIVING = 3

UNITS: year

: f change_in_driving_distance = (Desired_annual_driving_distance-Annual_Driving_Distance_per_capita)/ADJESTMENT_TIME_OF_DRIVING

UNITS: km/year/person/years

: c FRACTIONAL_INCREASE_RATE_OF_FUEL_TAX = 0.01

UNITS: 1/year

: f change_rate_fuel_tax = Increased_fuel_tax*FRACTIONAL_INCREASE_RATE_OF_FUEL_TAX

UNITS: euro/liter/years

: c TARGETED_IMPROVMENT_RATE = 1

UNITS: unitless

: c REFERENCE_FUEL_EFFICIENCY = 0.1

UNITS: liter/km

: c limit_to_innovation = "Improved_Fuel_Efficiency_(liter/km)"/REFERENCE_FUEL_EFFICIENCY

UNITS: unitless

: c historical_improvement_rate = -0.01

UNITS: unitless

: c fractional_improvement_rate = historical_improvement_rate*TARGETED_IMPROVMENT_RATE*limit_to_innovation

UNITS: unitless

: c PERIOD_OF_IMPLEMENTATION = 1

UNITS: year

: f fuel_efficiency_improvement = ("Improved_Fuel_Efficiency_(liter/km)"*fractional_improvement_rate)/PERIOD_OF_IMPLEMENTATION

UNITS: Liters/km/years

: c REFERENCE_FUEL_SUPPLY = 88.1*10^6

UNITS: ton/year

: c REFERENCE_PRICE = 0.4

UNITS: euro/liter

: c "SUPPLY_ELASTICITY_(Sensitivity_of_fuel_supply_to_price)" = 0.4

UNITS: unitless

: c fuel_supply = REFERENCE_FUEL_SUPPLY*(Fuel_Price/REFERENCE_PRICE)^"SUPPLY_ELASTICITY_(Sensitivity_of_fuel_supply_to_price)"

UNITS: ton/year

: c SWITCH_FUEL_EFFICIENCY_IMPROVEMENT = 1

UNITS: unitless

: c CONSTANT_FUEL_EFFICIENCY = 0.1

UNITS: liter/km

: c "fuel_efficiency_(l/km)" = CONSTANT_FUEL_EFFICIENCY*(1-SWITCH_FUEL_EFFICIENCY_IMPROVEMENT)+"Improved_Fuel_Efficiency_(liter/km)"*SWITCH_FUEL_EFFICIENCY_IMPROVEMENT

UNITS: liter/km

: c fuel_consumption_per_capita = Annual_Driving_Distance_per_capita*"fuel_efficiency_(l/km)"

UNITS: liter/year/person

: c LITER_TO_TON = 0.00074

UNITS: ton/Liters

: c "Total_fuel_consumption_(ton/year)" = fuel_consumption_per_capita*population*LITER_TO_TON

UNITS: ton/year

: c "fuel_demand/supply_ratio" = "Total_fuel_consumption_(ton/year)"/fuel_supply

UNITS: unitless

: c "SENSITIVITY_OF_PRICE_TO_DEMAND/SUPPLY_BALANCE" = 0.7

UNITS: unitless

: c "effect_of_demand/supply_balance_on_price" = "fuel_demand/supply_ratio"^"SENSITIVITY_OF_PRICE_TO_DEMAND/SUPPLY_BALANCE"

UNITS: unitless

: c REFERENCE_FUEL_TAX = 0.1

UNITS: euro/liter

: c SWITCH_FUEL_TAX = 1

UNITS: unitless

: c fuel_tax = Increased_fuel_tax*SWITCH_FUEL_TAX+REFERENCE_FUEL_TAX*(1-SWITCH_FUEL_TAX)

UNITS: euro/liter

: c indicated_fuel_price = fuel_tax+Fuel_Price*"effect_of_demand/supply_balance_on_price"

UNITS: euro/liter

: c PRICE_ADJUSTMENT_TIME = 3

UNITS: year

: f net_change_in_price = (indicated_fuel_price-Fuel_Price)/PRICE_ADJUSTMENT_TIME

UNITS: Euro/liter/years

: c fuel_cost_per_capita = fuel_consumption_per_capita*Fuel_Price

UNITS: Euro/year/person

: f net_change_of_annual_fuel_cost = (fuel_cost_per_capita-Annual_Fuel_Cost_per_capita)/YEAR

UNITS: Euro/year/people/years

: c FRACTIONAL_INCOME_GROWTH_RATE = 0.035

UNITS: unitless

: c INCOME_PERCEPTION_ADJUSTMENT_TIME = 1

UNITS: year

: f net_change_of_income =
(Expected_Income*FRACTIONAL_INCOME_GROWTH_RATE)/INCOME_PERCEPTION_ADJUSTMENT_TIME

UNITS: Euro/year/person/years

: c AVERAGE_VEHICLE_AGE = 11

UNITS: year

: f scrapping = Automobiles_in_Use/AVERAGE_VEHICLE_AGE

UNITS: Vehicle/years

: c "ratio_perceived/normal_road_congestion" = Perceived_Road_Congestion/NORMAL_ROAD_CONGESTION

UNITS: unitless

: c SENSITIVITY_OF_ROAD_ADJUSTMENT_TO_TRAFFIC_DENSITY = 0.5

UNITS: unitless

: c "pressure_to_increase_road_(to_reduce_traffic_density)" =
"ratio_perceived/normal_road_congestion"^SENSITIVITY_OF_ROAD_ADJUSTMENT_TO_TRAFFIC_DENSITY

UNITS: unitless

: c "ratio_roads/potential_roads" = Road_Networks/Potential_Roads

UNITS: unitless

: c SENSITIVITY_OF_ROAD_ADJUSTMENT_TO_ROAD_SATUATION = -0.7

UNITS: unitless

: c "NORMAL_RATIO_OF_ROAD/POTENTIAL_ROAD" = 0.1

UNITS: unitless

: c pressure_to_reduce_road_expension = ("ratio_roads/potential_roads"/"NORMAL_RATIO_OF_ROAD/POTENTIAL_ROAD")^SENSITIVITY_OF_ROAD_ADJUSTMENT_TO_ROAD_SATUATION

UNITS: unitless

: c planned_road_adjustment = Road_Networks*"pressure_to_increase_road_(to_reduce_traffic_density)"*pressure_to_reduce_road_expension

UNITS: km

: c TIME_FOR_ROAD_ADJUSTMENT = 15

UNITS: year

: f road_construction = (planned_road_adjustment-Road_Networks)/TIME_FOR_ROAD_ADJUSTMENT

UNITS: km/year

: c LITER_TO_JOULE = 33

UNITS: J/liter

: c "Total_energy_consumption_(J/year)" = fuel_consumption_per_capita*population*LITER_TO_JOULE

UNITS: J/year

{ RUNTIME EQUATIONS }

: S Annual_Driving_Distance_per_capita(t) = Annual_Driving_Distance_per_capita(t - dt) + (change_in_driving_distance) * dt

UNITS: km/year/person

: S Annual_Fuel_Cost_per_capita(t) = Annual_Fuel_Cost_per_capita(t - dt) + (net_change_of_annual_fuel_cost) * dt

UNITS: Euro/year/people

: S Automobiles_in_Use(t) = Automobiles_in_Use(t - dt) + (Automobile_purchace - scrapping) * dt

UNITS: Vehicle

: S Expected_Income(t) = Expected_Income(t - dt) + (net_change_of_income) * dt

UNITS: Euro/year/person

: S Fuel_Price(t) = Fuel_Price(t - dt) + (net_change_in_price) * dt

UNITS: Euro/liter

: S "Improved_Fuel_Efficiency_(liter/km)"(t) = "Improved_Fuel_Efficiency_(liter/km)"(t - dt) +

(fuel_efficiency_improvement) * dt

UNITS: liter/km

: S Increased_fuel_tax(t) = Increased_fuel_tax(t - dt) + (change_rate_fuel_tax) * dt

UNITS: euro/liter

: S Perceived_Road_Congestion(t) = Perceived_Road_Congestion(t - dt) + (adjustment_of_perception) * dt

UNITS: 1/year

: S Potential_Roads(t) = Potential_Roads(t - dt) + (- road_construction) * dt

UNITS: km

: S Road_Networks(t) = Road_Networks(t - dt) + (road_construction) * dt

UNITS: km

: c REFERENCE_INCOME_PER_CAPITA = 8000*0.9

UNITS: euro/year/person

: c automobiles_per_capita = Automobiles_in_Use/population

UNITS: vehicle/person

: c road_congestion = ((Annual_Driving_Distance_per_capita/automobiles_per_capita)*Automobiles_in_Use)/Road_Networks

UNITS: km/km/year

: f adjustment_of_perception = (road_congestion-Perceived_Road_Congestion)/CONGESTION_PERCEPTION_ADJUSTMENT_TIME

UNITS: 1/year/years

: c effects_of_road_networks_on_purchase_rate = (Road_Networks/REFERENCE_ROAD_NETWORKS)^SENSITIVITY_OF_CAR_PURCHASE_TO_ROAD_NETWORKS

UNITS: unitless

: c market_saturation = MAX(automobiles_per_capita/REFERENCE_AUTOBILES_PER_CAPITA, 1)

UNITS: unitless

: f Automobile_purchace = Automobiles_in_Use*(FRACTIONAL_INCREASE_RATE*effects_of_road_networks_on_purchase_rate/market_saturation)/YEAR

UNITS: Vehicle/years

: c Annual_income_per_capita = REFERENCE_INCOME_PER_CAPITA*(1-SWITCH_INCOME_GROWTH)+Expected_Income*SWITCH_INCOME_GROWTH

UNITS: Euro/year/person

: c share_of_income_on_fuel_cost = Annual_Fuel_Cost_per_capita/Annual_income_per_capita

UNITS: unitless

: c effect_of_fuel_cost_on_driving_demand = (share_of_income_on_fuel_cost/NORMAL_SHARE_OF_IMCOME_ON_FUEL_COST)^SENSITIVITY_OF_DRIVING_DEMAND_TO_FUEL_COST

UNITS: unitless

: c effects_of_road_networks_on_driving_demand = SWITCH_ROAD_NETWORKS_EFFECT*((Road_Networks/REFERENCE_ROAD_NETWORKS)^SENSITIVITY_OF_DRIVING_DEMAND_TO_ROAD_NETWORKS)+(1-SWITCH_ROAD_NETWORKS_EFFECT)

UNITS: unitless

: c Desired_annual_driving_distance = Annual_Driving_Distance_per_capita*effect_of_fuel_cost_on_driving_demand*effects_of_road_networks_on_driving_demand

UNITS: km/year/person

: f change_in_driving_distance = (Desired_annual_driving_distance-Annual_Driving_Distance_per_capita)/ADJESTMENT_TIME_OF_DRIVING

UNITS: km/year/person/years

: f change_rate_fuel_tax = Increased_fuel_tax*FRACTIONAL_INCREASE_RATE_OF_FUEL_TAX

UNITS: euro/liter/years

: c limit_to_innovation = "Improved_Fuel_Efficiency_(liter/km)"/REFERENCE_FUEL_EFFICIENCY

UNITS: unitless

: c fractional_improvement_rate = historical_improvement_rate*TARGETED_IMPROVMENT_RATE*limit_to_innovation

UNITS: unitless

: f fuel_efficiency_improvement = ("Improved_Fuel_Efficiency_(liter/km)"*fractional_improvement_rate)/PERIOD_OF_IMPLEMENTATION

UNITS: Liters/km/years

: c REFERENCE_FUEL_SUPPLY = 88.1*10^6

UNITS: ton/year

: c fuel_supply = REFERENCE_FUEL_SUPPLY*(Fuel_Price/REFERENCE_PRICE)^"SUPPLY_ELASTICITY_(Sensitivity_of_fuel_supply_to_price)"

UNITS: ton/year

: c "fuel_efficiency_(l/km)" = CONSTANT_FUEL_EFFICIENCY*(1-SWITCH_FUEL_EFFICIENCY_IMPROVEMENT)+"Improved_Fuel_Efficiency_(liter/km)"*SWITCH_FUEL_EFFICIENCY_IMPROVEMENT

UNITS: liter/km

: c fuel_consumption_per_capita = Annual_Driving_Distance_per_capita*"fuel_efficiency_(l/km)"

UNITS: liter/year/person

: c "Total_fuel_consumption_(ton/year)" = fuel_consumption_per_capita*population*LITER_TO_TON

UNITS: ton/year

: c "fuel_demand/supply_ratio" = "Total_fuel_consumption_(ton/year)"/fuel_supply

UNITS: unitless

: c "effect_of_demand/supply_balance_on_price" =

"fuel_demand/supply_ratio"^"SENSITIVITY_OF_PRICE_TO_DEMAND/SUPPLY_BALANCE"

UNITS: unitless

: c fuel_tax = Increased_fuel_tax*SWITCH_FUEL_TAX+REFERENCE_FUEL_TAX*(1-SWITCH_FUEL_TAX)

UNITS: euro/liter

: c indicated_fuel_price = fuel_tax+Fuel_Price*"effect_of_demand/supply_balance_on_price"

UNITS: euro/liter

: f net_change_in_price = (indicated_fuel_price-Fuel_Price)/PRICE_ADJUSTMENT_TIME

UNITS: Euro/liter/years

: c fuel_cost_per_capita = fuel_consumption_per_capita*Fuel_Price

UNITS: Euro/year/person

: f net_change_of_annual_fuel_cost = (fuel_cost_per_capita-Annual_Fuel_Cost_per_capita)/YEAR

UNITS: Euro/year/people/years

: f net_change_of_income =
(Expected_Income*FRACTIONAL_INCOME_GROWTH_RATE)/INCOME_PERCEPTION_ADJUSTMENT_TIME

UNITS: Euro/year/person/years

: f scrapping = Automobiles_in_Use/AVERAGE_VEHICLE_AGE

UNITS: Vehicle/years

: c "ratio_perceived/normal_road_congestion" = Perceived_Road_Congestion/NORMAL_ROAD_CONGESTION

UNITS: unitless

: c "pressure_to_increase_road_(to_reduce_traffic_density)" =
"ratio_perceived/normal_road_congestion"^SENSITIVITY_OF_ROAD_ADJUSTMENT_TO_TRAFFIC_DENSITY

UNITS: unitless

: c "ratio_roads/potential_roads" = Road_Networks/Potential_Roads

UNITS: unitless

: c pressure_to_reduce_road_expension =
("ratio_roads/potential_roads"/"NORMAL_RATIO_OF_ROAD/POTENTIAL_ROAD")^SENSITIVITY_OF_ROAD_
ADJUSTMENT_TO_ROAD_SATUATION

UNITS: unitless

: c planned_road_adjustment =
Road_Networks*"pressure_to_increase_road_(to_reduce_traffic_density)"*pressure_to_reduce_road_expension

UNITS: km

: f road_construction = (planned_road_adjustment-Road_Networks)/TIME_FOR_ROAD_ADJUSTMENT
{UNIFLOW}

UNITS: km/year

: c "Total_energy_consumption_(J/year)" = fuel_consumption_per_capita*population*LITER_TO_JOULE

UNITS: J/year

{ TIME SPECS }

STARTTIME=1970

STOPTIME=2050

DT=0.25

INTEGRATION=EULER

RUNMODE=NORMAL

PAUSEINTERVAL=0

{ The model has 84 (84) variables (array expansion in parens).

In root model and 0 additional modules with 0 sectors.

Stocks: 10 (10) Flows: 10 (10) Converters: 64 (64)

Constants: 38 (38) Equations: 36 (36) Graphicals: 0 (0) }