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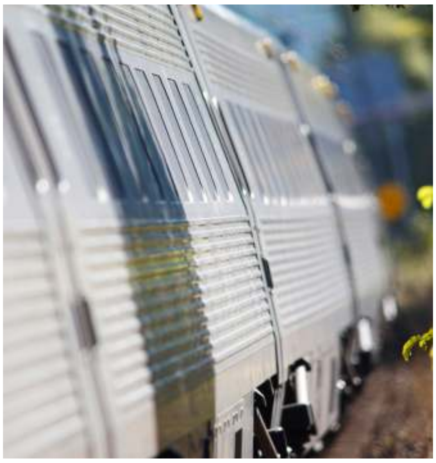

Rebound effects of energy efficiency measures in the transport sector in Sweden

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Abstract

Rebound effects represent the difference between anticipated or projected energy savings and the real energy saving in relation to, for example, implemented policy measures aimed at improving energy efficiency.

Rebound effects in the transport sector may counteract policy measures so that goals related to energy or emissions are not achieved, or achievement is greatly delayed.

This comprehensive report examines the presence of rebound effects within the transport sector and while the aim was to provide a full review of the issue, for some transport areas it was not possible to find any studies on rebound effects. Those areas are identified as having knowledge gaps.

We summarize the literature for rebound effects for passenger vehicles, technological developments, freight transports, public lighting, aviation, waterborne transports and for indirect, economy-wide effects, and also discuss rebound effects in aspects of environmental awareness and in the transport and community planning.

The existing literature suggests that rebound effects exist to varying degrees and that there is a high risk of energy efficiency measures transferring transport energy savings into other transport modes, sectors or energy services. Consequently, rebound effects should be included when calculating whether Sweden will reach its climate and energy goals.

Keywords: passenger transport, lighting, freight, aviation, waterborne transport, transport planning

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Referat

Rekyleffekter är skillnaden mellan den förväntade eller beräknade energibesparingen och den verkliga energibesparingen för olika typer av åtgärder. Om detta inte tas med i beräkningar kan rekyleffekter motverka politiska åtgärder så att mål relaterade till energi och utsläpp inte uppnås eller blir försenade.

Målet med denna rapport är att göra en litteraturöversikt och att identifiera kunskapsluckor. Följande områden tas upp: fordon och bränslen, persontransporter, vägtransporter, luftfart, godstransporter, sjöfart, teknisk utveckling och utomhusbelysning. Direkta, indirekta och ekonomiövergripande rekyleffekter tas upp och även exempel på rekyleffekter i transportplaneringen. Rekyleffekter är också diskuterade ur aspekter av miljömedvetande och hur de hanteras i transport- och samhällsplaneringen. Vi har också identifierat områden som saknar väsentlig information om rekyleffekter.

Sammanfattningsvis så tyder våra resultat på att rekyleffekter förekommer i olika storlekar och att det finns stor risk att energieffektiviseringsåtgärder inom transportsektorn överför energibesparingarna till andra typer av transportslag, sektorer eller energitjänster vilket kan resultera i förlorade eller inga energibesparingar eller ännu värre, en ökad energikonsumtion. Därför bör rekyleffekter beräknas för att Sverige skall nå sina klimat- och energimål. Detta gäller speciellt inom transportsektorn där rekyleffekterna antas vara särskilt stora inom vissa transportslag och över tiden.

Nyckelord: persontransporter, belysning, godstransporter, flyg, sjöfart, transport planering

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Foreword

This is the final report for the project “Rebound effects of energy efficiency measures in the transport sector in Sweden” (project number 201545, dnr. 2013/0493-7.2) funded by the Swedish Energy Agency’s research programme “Energy efficiency within the transport sector”. The official in charge at the Swedish Energy Agency was Catharina Norberg.

The project leader, Annika Jägerbrand, initiated the project.

Annika Jägerbrand, Joanna Dickinson, Anna Mellin, Mattias Viklund, all the Swedish National Road and Transport Research Institute (VTI), and Staffan Dahlberg, Stockholm, jointly conducted the project by writing separate or joint parts of the report. The order of author names for the separate sections is based on contribution to the text or responsibility for the text.

Håkan Hellgren, Unswank consult, assisted with transcribing interviews.

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Stockholm, June 2014

Annika Jägerbrand
Project leader

Process for quality review

Internal peer review was performed on 13 June 2014 by Megersa Abate, VTI. Annika Jägerbrand made alterations to the final manuscript of the report on 16 June 2014. Research director Kerstin Robertson examined and approved the report for publication on 17 June 2014. The conclusions and recommendations expressed are those of the authors' and do not necessarily reflect the opinion of VTI as an authority.

Process för kvalitetsgranskning

Intern peer review har genomförts den 13 juni 2014 av Megersa Abate, VTI. Annika Jägerbrand har genomfört justeringar av slutligt rapportmanus den 16 juni 2014. Forskningschef Kerstin Robertson har därefter granskat och godkänt publikationen för publicering den 17 juni 2014. De slutsatser och rekommendationer som uttrycks är författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

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Rebound effects of energy efficiency measures in the transport sector in Sweden

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Summary

Transport accounts for 25–30% of global energy-related CO_2 emissions and is therefore a significant and growing contributor to total greenhouse gas (GHG) emissions. In Sweden, the transport sector accounts for about 25% of total energy consumption and in 2012 was responsible for 33% of total GHG emissions. It is therefore important to decrease GHG emissions and increase energy efficiency within the transport sector in order to reach national climate and energy goals, e.g. a fossil-independent transport fleet by 2030 and energy production with no net GHG emissions to the atmosphere. A number of measures and instruments are currently in place to reduce energy consumption and GHG emissions in Sweden.

Rebound effects represent the difference between anticipated or projected energy savings and the real energy saving in relation to, for example, implemented policy measures aimed at improving energy efficiency. Energy efficiency improvements thus do not necessarily lead to lower overall energy demand, at least compared with unchanged use of the service or goods. Such rebound effects in the transport sector may counteract policy measures so that goals related to energy or emissions are not achieved, or achievement is greatly delayed.

This comprehensive report examines the presence of rebound effects within the transport sector. It covers the areas of vehicle and fuel shifts, aviation, freight and waterborne transport, technological developments, artificial lighting and indirect and economy-wide rebound effects, and provides some examples of rebound effects in transport planning. The aim was to provide a full review of the issue, but for some transport areas it was not possible to find any studies on rebound effects. Those areas are identified as having knowledge gaps. The report also presents available data that can be used for analysis of Swedish rebound effects and results from two interviews with transport planners.

Calculated rebound effects and their magnitude depend on input and output data, time scale, geographical scale, economic situation and study boundaries. There is currently no common agreed methodology on how to measure rebound effects, except as the ratio of potential to actual energy savings.

For **passenger vehicles**, the direct rebound effect is reported to be in the range of 10–70% in Europe and 10–30% in the USA, and developing countries with a large unmet demand for energy will generate a high rebound (or backfire) effect. A direct rebound effect of 10–30% has been suggested for Sweden. However, the effects of **technological developments** in the Swedish car fleet in 1975–2002 resulted in a 35% net decrease in fuel consumption, but 65% of the efficiency increase was negated by the counteracting effects of consumer demand, for example for increased passenger space and horsepower. Furthermore, dieselization of the Swedish car fleet probably increased the distance driven.

Studies of direct rebound effects in **freight transport** are few. Estimates indicate rebound effects of approx. 13–22% in the short run and 12–45% in the long run, but there are considerable variations between different studies and it is unknown how realistic these figures are for Swedish conditions.

Public lighting is the only sector within the transport area with extremely long time-series of data available, and clearly shows strong rebound effects (and backfires) in time, repeatedly happening in direct correlation with technological revolutions. It is unknown, but possible, that light sales might be levelling off, directly mitigating the rebound effects of the current revolution in solid state lighting.

For **transport and community planning,** we were unable to obtain any empirical evidence of a rebound effect, except for road investments aimed at reducing congestion and travel times.

For **aviation**, we found only one study, showing a rebound effect of 19% for aircraft in the USA. For **waterborne transport,** there seems to be a lack of data, but it seems plausible that rebound effects exist e.g. in passenger transport and short sea shipping, but also when considering modal shifts in a system analysis approach.

As regards **indirect and economy-wide effects**, rebound effects varied between 10–100%, but are suggested to be mostly significantly less than 100%.

Environmental awareness may help avoid indirect rebound effects, but it might be more difficult to avoid direct rebound effects, even when consumers have pro-environmental attitudes. A number of aspects need to be considered to fully understand consumer responses to changes in energy efficiency or energy prices, and thus the rebound effects, but these have not yet been studied in a Swedish context.

To summarise, the existing literature suggests that rebound effects exist to varying degrees and that there is a high risk of energy efficiency measures transferring transport energy savings into other transport modes, sectors or energy services, resulting in lost or zero energy savings or, even worse, increased energy consumption. Consequently, rebound effects should be included when calculating whether Sweden will reach its climate and energy goals, especially within the transport sector, where there are indications that rebound effects are particularly large within specific transport modes and over time.

Unfortunately, the rebound effects are currently unknown in most cases and many factors can affect their magnitude. For example, aviation, waterborne transport, transport planning, indirect rebound effects, time dimensions of rebound effects and transport, and aspects of human behaviour and transport were all identified as lacking substantial information on rebound effects. Therefore, this report identified some areas for future studies in a Swedish context.

Rekyleffekter av energieffektiviseringar inom transportsektorn i Sverige

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Sammanfattning

Transporter står för 25–30 procent av de globala, energirelaterade CO_2-utsläppen och är därför ett betydande och växande bidrag till de totala GHG-utsläppen (GHG = växthusgaser). I Sverige står transportsektorn för cirka 25 procent av den totala energikonsumtionen och under 2012 var transportsektorns del 33 procent av de totala GHG-utsläppen. Eftersom transportsektorn står för en så pass stor andel av CO_2 utsläppen är det viktigt att minska utsläppen och att öka energieffektiviseringen för att Sverige ska kunna nå uppsatta klimat- och energimål, till exempel en fossilfri fordonsflotta till år 2030. Det finns redan nu ett antal åtgärder satta i system för att verka för en minskad energikonsumtion och för att reducera CO_2-utsläppen i Sveriges transportsektor.

Rekyleffekter är skillnaden mellan de förväntade eller beräknade energibesparingarna och den verkliga energibesparingen för olika typer av åtgärder. Följaktligen, när åtgärder för energieffektivisering genomförs inom ett område eller en sektor är det inte säkert att det leder till lägre total energianvändning. Om detta inte tas med i beräkningen kan rekyleffekter motverka politiska åtgärder så att mål relaterade till energi och utsläpp inte uppnås eller blir försenade.

Det finns ingen allmänt vedertagen metodik om hur rekyleffekter mäts förutom av kvoten av beräknad energibesparing gentemot reell energibesparing. Rekyleffekter och dess storlek är beroende av indata, tidsramar, geografiska faktorer, ekonomiska situationer, statistisk analysmetodik och analysens begränsningar.

Den här rapporterade studien har med ett brett perspektiv undersökt förekomsten av rekyleffekter inom transportsektorn. Följande områden tas upp: fordon och bränslen, persontransporter, vägtransporter, luftfart, godstransporter, sjöfart, teknisk utveckling, och utomhusbelysning. Direkta, indirekta och ekonomiövergripande rekyleffekter tas upp och även exempel på rekyleffekter i transportplaneringen. Målet med denna rapport är att göra en litteraturöversikt och att identifiera kunskapsluckor. Utöver detta presenterar rapporten tillgängligt dataunderlag som kan användas för analyser av rekyleffekter i Sverige.

För **personbilar** visar litteraturgenomgången på att de direkta rekyleffekterna är i storleken 10–70 procent i Europa och 10–30 procent i USA och att utvecklingsländer med ett stort otillfredsställt energibehov kommer att generera en högre rekyleffekt eller till med en så kallad ”backfire” med en ökning av energiuttaget. För Sverige har en direkt rekyleffekt på 10–30 procent föreslagits men effekten av den **tekniska utvecklingen** av den svenska fordonsflottan 1975–2002 visade att ökade konsument-krav som till exempel ökade passagerarutrymmen och kraftfullare motorer åt upp 65 procent av energieffektiviseringen. Utöver detta så finns det risk att övergången till dieselmotorer inom svenska bilflottan har lett till ökad körsträcka. Det finns få studier

av direkta rekyleffekter av åtgärder avseende **godstransporter** men uppskattningen är att rekyleffekten i ett kort perspektiv är ca 13–22 procent och i ett längre perspektiv 12–45 procent. Det är dock stor variation mellan de olika studierna och det är okänt hur realistiska dessa siffror är för svenska förhållanden.

Utomhusbelysning är det enda området inom transportsektorn med extremt långa tidsserier av data och de visar stora rekyleffekter och backfire (det vill säga att energianvändningen totalt ökar istället för minskar efter införd åtgärd) över flera århundranden. Rekyleffekterna uppkommer i direkt korrelation med de teknologiska revolutioner som skett under de senaste seklen. Det är okänt men möjligt att försäljning av utomhusbelysning håller på att plana ut vilket skulle kunna motverka framtida rekyleffekter för den i dagsläget pågående snabba revolutionen inom belysningsområdet.

För **transport- och samhällsplanering** har vi inte kunnat lägga fram några empiriska bevis för att rekyleffekter existerar i den vetenskapliga litteraturen förutom för väginvesteringar vars mål är att minska trafikstockningar och restider.

För **luftfart** har vi enbart funnit en studie som visar en rekyleffekt på 19 procent för flygplan i USA.

För **vattenburna transporter** och sjöfart så saknas relevanta studier. Det verkar dock troligt att rekyleffekter finns inom till exempel passagerartransporter och närsjöfrakt men också om man räknar med rekyleffekter i ett transportöverslagsgripande perspektiv.

När det gäller **indirekta och ekonomiövergripande rekyleffekter** så kan de vara mellan 10–100 procent och det har föreslagits att rekyleffekterna för det mesta är mindre än 100 procent, vilket betyder att åtgärderna bidrar till en energieffektivisering.

Miljömedvetande kan leda till att man undviker indirekta rekyleffekter men det kan bli svårt att undvika direkta rekyleffekter även när konsumenter är miljömedvetna. Flera aspekter behöver beaktas för att till fullo förstå konsumentreaktioner när det gäller energieffektivisering eller energipriser och därmed rekyleffekterna, men dessa har inte studerats under svenska förhållanden.

Sammanfattningsvis så tyder våra resultat på att rekyleffekter förekommer i olika storlekar och att det finns stor risk att energieffektiviseringsåtgärder inom transportsektorn överför energibesparingarna till andra typer av transportslag, sektorer eller energitjänster vilket kan resultera i förlorade eller inga energibesparingar eller ännu värre, en ökad energikonsumtion. Därför bör rekyleffekter beräknas för att Sverige skall nå sina klimat- och energimål. Detta gäller speciellt inom transportsektorn där rekyleffekterna antas vara särskilt stora inom vissa transportslag och över tiden.

Olyckligtvis så är rekyleffekterna i Sverige okända för de allra flesta transportslag och dessutom påverkar många faktorer storleken av rekyleffekten. Exempelvis så saknar följande områden väsentlig information om rekyleffekter: luftfart, sjöfart, transportplanering, indirekta rekyleffekter, tidsaspekter på rekyleffekter inom transporter samt konsumentbeteende. Vi har därför i detta projekt även identifierat några områden för framtida studier som anses viktiga för Sveriges del.

1 Introduction

1.1 Purpose and goal

Author: Annika Jägerbrand

The main purpose of the project was to estimate the influence of rebound effects in the transport sector in Sweden, with the focus on energy efficiency and energy efficiency measures.

Specific objectives of this project were to:

- Identify commonly applied measures in the transport sector (both passenger and freight) aimed at improving the energy efficiency.
- Identify the kinds of rebound effects that might affect or be relevant for the established national aims and goals for climate and energy.

The project goal was to compile a report that summarised existing publications within the research area from a national standpoint, perform an inventory of easily available relevant data and collect some qualitative data based on interviews with a few relevant officials within the area of transport infrastructure planning.

Due to time restrictions in the project, analyses of the literature had to be restricted to focusing on finding publications within the transport sector that specifically included rebound effects. We are aware that within some research areas there is a vast amount of published material dealing with e.g. fuel efficiency within passenger transport, energy efficiency of various policy measures, energy system analyses and/or studies dealing with specific economic aspects of rebound effects.

1.2 Background

Author: Annika Jägerbrand

Transport activities are continuously increasing globally, with large increases anticipated to occur in mainly underdeveloped countries in the future (e.g. Kahn Ribeiro et al., 2007). There are several problems associated with transport activities, for example air pollution, traffic fatalities and injuries, congestion and petroleum dependence, to mention a few. Thus, transport activities are challenging issues to deal with for planners and policymakers when aiming for more stable or sustainable development. Not all transport activities are harmful and non-sustainable, but the majority of transport relies on petroleum as a single fossil resource, causing substantial GHG and CO_2 emissions. Globally, most of the oil consumed is used in transport (International Energy Agency, 2009).

Transport accounts for 25-30% of global energy-related CO_2 emissions and is therefore a significant and growing contributor to total GHG emissions (OECD and ITF, 2009; International Energy Agency, 2009). Two-thirds of transport CO_2 emissions come from road transport. Growth rates of transport energy use in OECD countries have fallen during 2000-2006, while growth rates in non-OECD countries are still increasing (Table 1). Given present trends, IEA projects that worldwide transport energy use and CO_2 emissions will increase by nearly 50% by 2030 and more than 80% by 2050 (International Energy Agency, 2009). Car ownership, trucking activities and air travel in particular have the potential to increase in the order of threefold or four-fold amounts.

Table 1 Growth rate of transport energy use in OECD and non-OECD countries 1990-2006. Adopted from International Energy Agency (2009).

	OECD				Non-OECD			
Year period	1990-1995	1995-2000	2000-2006	1990-2006	1990-1995	1995-2000	2000-2006	1990-2006
Growth rate of transport energy use	2.1 %	2.1 %	1.2 %	1.8 %	1.1 %	2.6 %	4.3 %	2.8 %

Despite worldwide efforts to mitigate CO_2 emissions, fossil fuel burning and cement production increased emissions by 2.1% in 2012, yielding record high CO_2 emissions of 9.7±0.5 GtC, and with similar increases projected for 2013 (i.e. 2.1% increase in emissions) (Global Carbon Budget 2014). Worldwide CO_2 emissions in 2012-2013 were nearly 60% higher than in 1990. The year 1990 is an important base year due to its central part in the Kyoto Protocol.

The Kyoto Protocol, initiated by the United Nations Framework Convention on Climate Change (UNFCCC), sets binding obligations on many developed countries to reduce GHG emissions in two commitment periods, 1990-2008/2012 and 2013-2020 (e.g. UNFCCC, 2014a). In the first period, Sweden as a member of EU has committed to reach a decrease in GHG emissions of 8% during 2008-2012 compared with the base year 1990 (UNFCCC 2014b) and a decrease in GHG emissions (excluding Land Use, Land-Use Change and Forestry, LULUCF) by 21% or 15 billion tonnes (±5.4%) between 1990-2012 (Swedish Environmental Protection Agency, 2014).

However, GHG emissions from international bunkers in the aviation and marine sector during the same period increased by 62%, and 159%, respectively (yielding a total increase in GHG emissions of 4.45 billion tonnes CO_2-equivalents for 1990-2012), but are not included in the reported GHG emissions according to the Kyoto Protocol. Similarly, GHG emissions from international trade (production on goods and services traded in other countries, but consumed in Sweden) are not included in the National Inventory Report, despite the fact that for e.g. Sweden, the emissions transfer due to trading was an estimated average of 29 $MtCO_2$ per year in 1990-2008 (Peters et al., 2010).

Swedish commitments adopted at the national level for energy and climate goals include:

- 20% reduced energy use for all sectors between 2008-2020 (Prop. 2008/09:163). This goal is also one of the EU 20-20-20 targets (European Commission, 2014).
- 40% reduced GHG emissions between 1990-2020 for sectors not affected by the emission trading system EU ETS (prop. 2008/09:162). This is equal to a reduction of 20 million tonnes CO_2-equivalents.
- Sustainable energy should account for 50% of Sweden's total energy use in 2020 (prop. 2008/09:163).
- By the year 2050, Sweden should have sustainable and resource-efficient energy production (all sectors) with no net GHG emissions into the atmosphere (Miljödepartementet, 2014). This goal is in line with the EU Roadmap for moving to a competitive low carbon economy by 2050 (COM 2011).

Climate- and energy-related goals specific for the transport sector can be found in the proposition 2008/09:162 and state that the transport sector shall contribute to reach limited climate change (one of the national environmental quality objectives) by a successive increase in energy efficiency and by termination of fossil fuel dependence. Furthermore, the proposition states (2008/09:162) "[by the] *year 2030, Sweden should have a transport fleet independent from fossil fuels*".

This report focuses on a range of energy efficiency measures within transport and transport-related areas of relevance. However, within the scope of the project we were unable to evaluate and determine whether Swedish policy goals and measures are efficient, economically viable and other such aspects. Instead, we focused on systematically collecting literature (scientific and non-scientific publications, relevant information and in some cases data) concerning the energy efficiency and energy efficiency measures for transport in the perspective of non-optimal energy savings or unwanted effects, such as rebound effects. In this report, we define rebound effects in accordance with Matos & Silva (2011) as "*the difference between the projected energy savings and the actual energy savings resulting from the increased energy efficiency*".

In some cases where there are few studies previously published, we discuss rebound effects as examples or in relation to other knowledge within the area (e.g. transport planning and waterborne transport). One important finding is that rebound effects have been widely studied within a few specific areas, while data or background knowledge is lacking for other areas. Hence, we identified some research areas that may be relevant for future studies.

We focused on transport areas that are of interest from a Swedish perspective, such as vehicles and fuels, aspects of transport planning, transport policy, aviation, freight, waterborne transport, artificial lighting and also human behaviour, technological development and indirect rebound effects. However, flexible mechanism measures (e.g. clean development mechanism, CDM) and their possible unwanted energy effects were considered to be beyond the scope of this report, even though such mechanisms are included in the calculations by the Swedish authorities to reduce the national GHG emissions.

Chapter 1 provides background information on Sweden's energy and climate goals, defines rebound effects and how they are measured and then describes rebound effects as a consequence of human behaviour. Chapter 2 describes methods, Chapter 3 concerns direct rebound effects and vehicles, Chapter 4 deals with freight road transport, Chapter 5 deals with aviation and waterborne transports, Chapter 6 artificial lighting, Chapter 7 technological developments, Chapter 8 measures in local transport planning and Chapter 9 deals with indirect rebound effects. Finally, Chapter 10 discusses the findings in short sub-sections and from an overall perspective and draws some conclusions. Two appendixes are attached, an inventory of available data for future analysis of rebound effects (A), and results from interviews with two transport planners (B).

1.3 Trends in energy use and GHG emissions from the Swedish transport sector 1990-2012

Author: Annika Jägerbrand

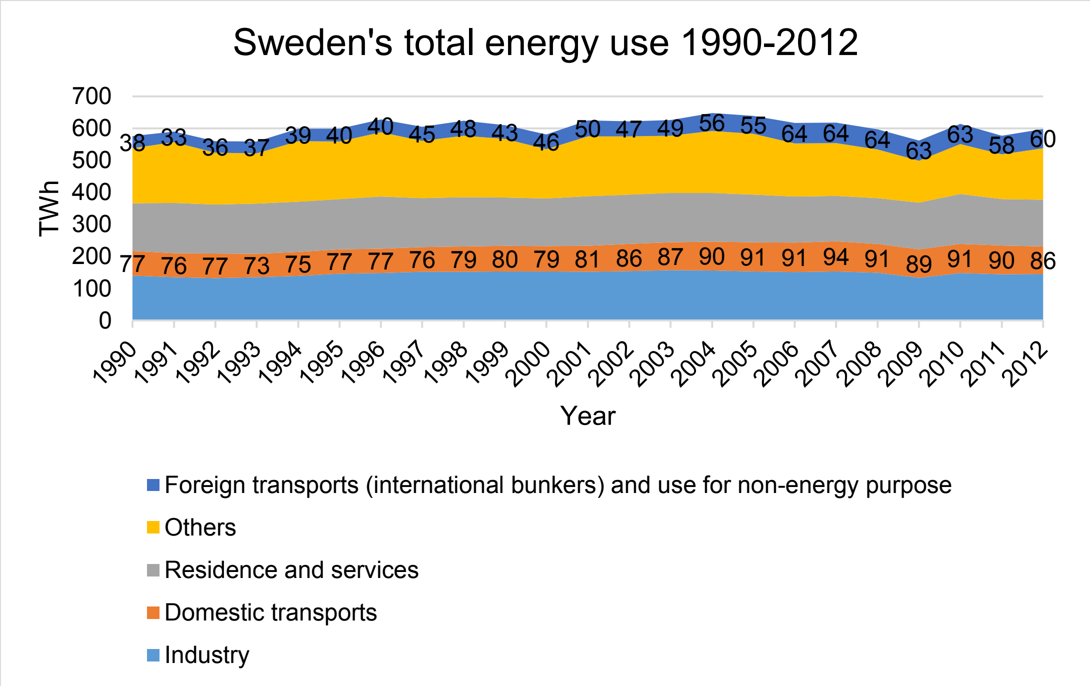

Figure 1 Total energy use in Sweden (TWh) 1990-2012. Data labels show domestic transport and foreign transport (international bunkers) and use for non-energy purposes. Data from Swedish Energy Agency (2014).

In Sweden, the transport sector accounts for about 25% of total energy consumption (Swedish Energy Agency 2013a), and in 2012, the transport sector was responsible for 33% of total GHG emissions (Swedish Environmental Protection Agency, 2014). Energy use in domestic transportation increased from 77 to 86 TWh per year between 1990-2012, while energy use for foreign transport (international bunkers) and use for non-energy purposes increased from 38 to 60 TWh per year in the same period (Figure 1).

In 2012, GHG emissions from the transport sector were almost at the same level as in 1990 (19.272 million tonnes CO_2-equivalents in 1990 and 19.106 million tonnes CO_2-equivalents in 2012) (Swedish Energy Agency 2013a).

GHG emissions from road transport comprise 31% of the national GHG emissions and have increased by 2% since 1990. For all years, road transport is the single largest GHG emissions source in Sweden (Swedish Environmental Protection Agency, 2014), and the trend for road transport to be the dominant GHG emissions source within all transports has been more or less constant since 1990 (Figure 2). Road transport accounted for 17.9 million tonnes CO_2-equivalents in 2012 (Figure 2).

The GHG emissions in road transportation come mainly from passenger car transport and, to a lesser degree, from heavy duty vehicles (Figure 3). GHG emissions from passenger transport in Sweden varied somewhat during 1990-2012 but have decreased in the recent years, to the same level as in 1990, while GHG emissions from heavy and light duty vehicles have increased (Figure 3).

More specifically, passenger transport resulted in total emissions of 292.787 million tonnes CO_2-equivalents and a change of -14% for the period 1990-2012, whereas heavy duty vehicles accounted for 88.560 million tonnes CO_2-equivalents and an increase of 44% during the same period (Table 2). Furthermore, while international bunkers are not included in the GHG national inventory to UNFCCC, it is clear that those GHG emissions constitute a large and growing part of the emissions, resulting in total emissions of 157.577 million tonnes CO_2-equivalents and an increase of approx. 123% between 1990 and 2012 (Table 2).

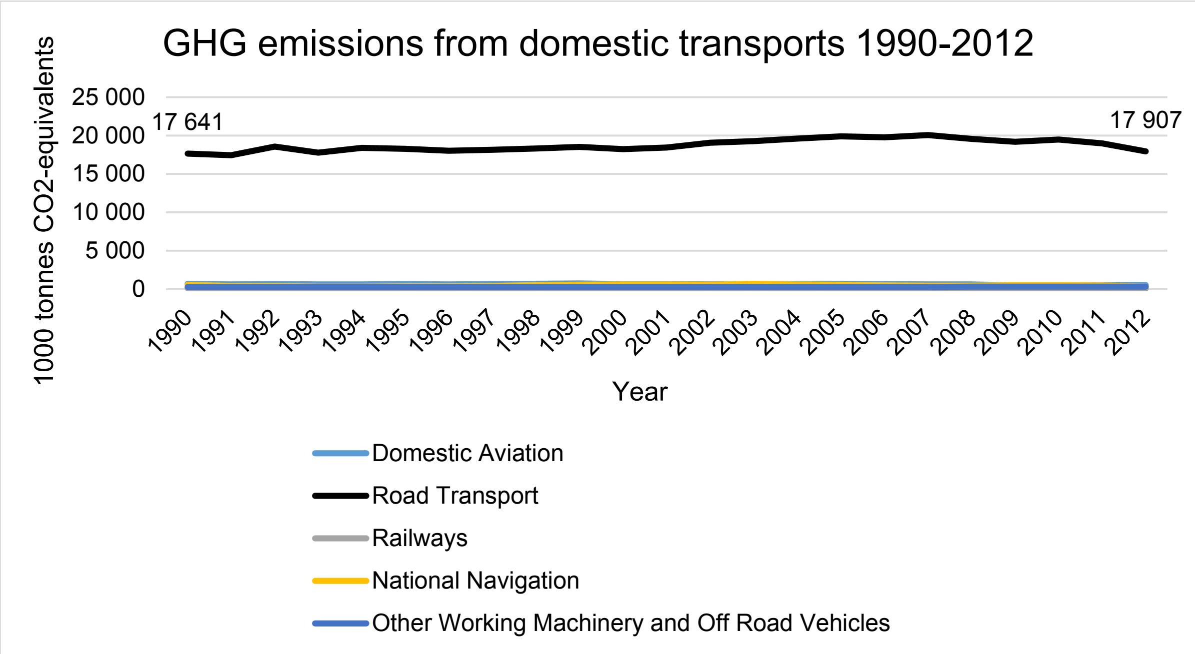

Figure 2 GHG emissions (1000 tonnes CO_2-equivalents) for domestic transport 1990-2012 in Sweden. Data labels show GHG emissions for road transport in 1990 and 2012, respectively. Data from Swedish Environmental Protection Agency (2014).

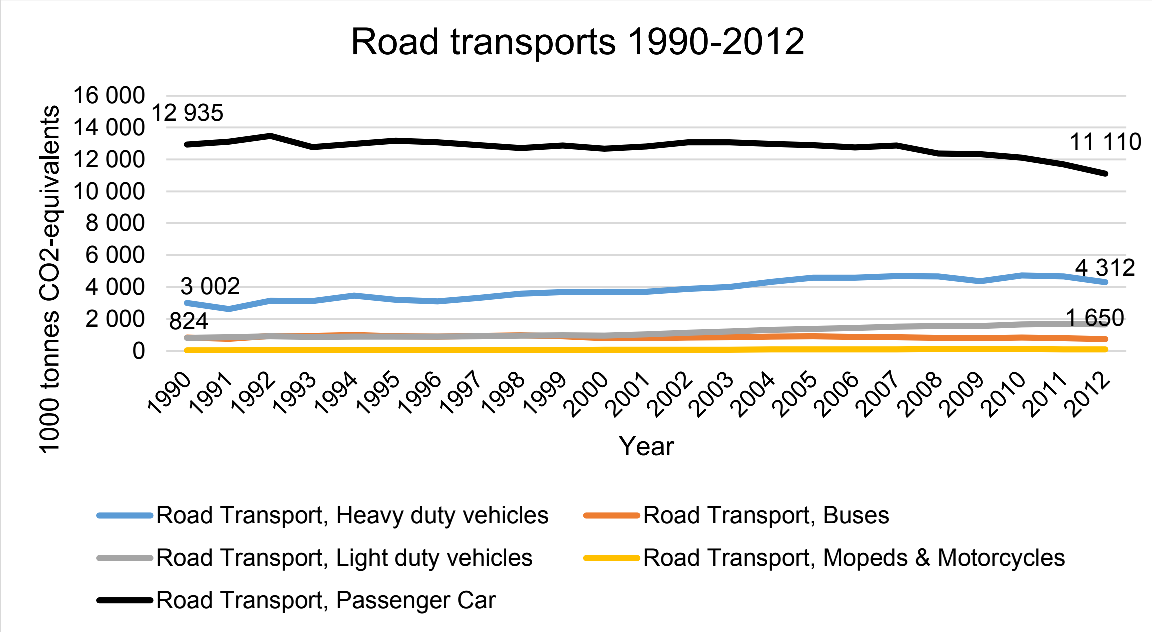

Figure 3 GHG emissions (1000 tonnes CO_2-equivalents) from domestic road transport 1990-2012 in Sweden. Data labels show GHG emissions for passenger car, heavy duty vehicle and light duty vehicle in 1990 and in 2012. Data from Swedish Environmental Protection Agency (2014).

Table 2 Total emissions 1990-2012, change 1990-2012, and percentage change 1990-2012 in GHG from domestic transport in Sweden, and from international bunkers 1990-2012. Adopted partly from Swedish Environmental Protection Agency (2014).

Emissions of Greenhouse Gases from Domestic Transport, 1000 tonnes CO_2-equivalents	Total emissions 1990-2012, 1000 tonnes CO_2-equivalents	Change 1990-2012	% change 1990-2012
Domestic Aviation	14,225	-164	-24%
Road Transport, Heavy duty vehicles	88,560	1,310	44%
Road Transport, Buses	19,958	-99	-12%
Road Transport, Light duty vehicles	27,267	826	100%
Road Transport, Mopeds & Motorcycles	1,682	53	124%
Road Transport, Passenger Cars	292,787	-1,825	-14%
Railways	1,854	-47	-42%
National Navigation	11,031	-246	-44%
Other Working Machinery and Off-road Vehicles	6,639	25	9%
Emissions of Greenhouse Gases from International Bunkers, 1000 tonnes CO_2-equivalents			
International bunkers - Aviation	40,455	840	62%
International bunkers - Marine	117,122	3,599	159%
Multilateral operations	25	3	6057%
Total domestic transport	464,003	-166	-1%
Total international bunkers	157,602	4,442	123%

1.4 Overview of measures aiming to increase energy efficiency in transport

Authors: Joanna Dickinson & Annika Jägerbrand

Internationally, much effort had been devoted to inventing, creating and implementing a range of measures aimed at increasing energy efficiency or reaching the goal of a sustainable transport sector. For example, Kahn Ribeiro et al. (2007) have written about transportation and mitigation technologies and strategies, as well as their mitigation potential, policies and measures.

In Sweden, the Swedish Transport Administration has produced a document which aims at reducing the energy use and climate change effects from the transport sector (Johansson et al., 2012). A later Swedish government official report in two parts deals in detail with how Sweden can accomplish a fossil-independent transport fleet by the year 2030 and no energy production with net GHG emissions to the atmosphere (SOU, 2013:84a, SOU, 2013:84b).

According to the Swedish Transport Administration (Johansson et al., 2012), the greatest potential for reducing the transport sector's energy and carbon footprint is reduced emissions from passenger cars. This can be achieved partly through improved energy efficiency and increased use of renewable energy. However, there are substantial variations in the fuel and energy needs within each transport mode depending on, for example, load rate or passenger factor, fuel usage, driving pattern and type of vehicle (SOU, 2013:84a).

Furthermore, the Swedish Transport Administration has pointed out that potential changes in community planning to accomplish reduced transport demand and a choice towards increased modal share of traveling by foot, bicycle and public transport instead of car are also essential to accomplish more energy-efficient passenger transport (Johansson et al., 2012). Railway may also take over certain travel from aviation.

For freight, the Swedish Transport Administration considers the contribution from more energy-efficient vehicles and renewable energy use to be approximately equally important in achieving more energy-efficient shipping and truck transport. Railroad and waterborne transport can help to reduce the transport sector's energy use and carbon footprint by taking care of the freight moved by road.

At present, most government authorities agree that Sweden will not reach the goals of a fossil-independent transport fleet by the year 2030 or energy production with no net GHG emissions to the atmosphere (for example Trafikanalys, 2013:4; SOU, 2013:84a; Trafikverket, 2014).

1.5 Economic instruments aiming at less energy consumption in transportation

Author: Joanna Dickinson

There are several definitions of policy instruments in the transport sector. One definition refers to policy measures aiming to influence the demand for travel and transportation and to utilise the existing transportation system more efficiently, for example with a reduced proportion travelling by car and increased proportion travelling by bicycle, pedestrian and public transport. "More effective" has a broad meaning, and includes resource efficiency in terms of, for example, energy and land use, as well as the use of financial resources for infrastructure (Trafikverket, 2012). Trafikverket (2012) categorises policy instruments as financial instruments (fees, taxes, emissions trading, subsidies, rebates), administrative (restrictions, principles of capacity allocation) and informative (ITS, Mobility Management). According to the Swedish Transport Administration (Trafikverket, 2012), such instruments aim to govern the use of capacity of the transport system.

In the Swedish context, a number of instruments are used today in the transport sector to reduce energy consumption and carbon footprint. Those that have existed for a long time are primarily carbon tax and exemption from fuel taxes for biofuels.

Recent years have seen several different policy instruments being introduced in order to reduce the GHG emissions and fuel consumption of passenger car transport (SOU, 2013:84a). These have the character of subsidies on the national and local level in the form of large tax breaks and other benefits to promote 'environment cars' (Kågeson, 2013). The state and local governments have tried since 2000 with various instruments to stimulate reduced consumption of fuel and the transition to biofuels and electricity in road transport by stimulating consumers to shift to such cars.

According to a government regulation adopted in 2004, 'environment cars' means flexible-fuel vehicles that can run on the renewable fuels ethanol (E85) or biogas or when driven on fossil fuel do not emit more than 218g CO_2 per km. Cars with automatic transmission have no upper limit as long as the same model with manual gears does not emit more than 218 CO_2 per km. Diesel and petrol cars that are not equipped for E85 or biogas and that emit under 120 g CO_2 per km are also labelled 'environment cars' (Kågeson, 2013).

The instruments used on national level have focused to a large extent on supporting the transition to biofuels and vehicles that can use those in a high proportion, but for some the goal has been to influence consumers to choose energy-efficient cars. Regarding fuel, the focus has been on low-level blends of ethanol and FAME[1] in petrol and diesel, and E85[2], ED95[3] and biogas. Support has been directed to both fuels and alternative vehicles.

In 2006, a special law with the aim of providing biofuel in higher concentrations was adopted. The industry responded to this by investing in tanks and pumps for E85, which gave parliament reason to introduce a subsidy for investments in equipment for the storage and sale of biogas.

Parliamentary decisions have introduced the following reported tax instruments used to promote road vehicles that can be powered by electricity or biofuels[4]:

- Reduced value of fringe benefits in 2002-2011. Company cars used by employees for private driving are offered large reductions in tax on this benefit in kind, and

[1] FAME = Fatty acid methyl esters, biodiesel usually obtained from vegetable oil.
[2] E85 = ethanol fuel blend of 85% denatured ethanol fuel and 15% petrol or other hydrocarbon. The exact ratio can vary somewhat.
[3] ED95 = "*ED95 designates a blend of 95% ethanol and 5% ignition improver; it is used in modified diesel engines where high compression is used to ignite the fuel, as opposed to the operation of gasoline engines, where spark plugs are used. This fuel was developed by Swedish ethanol producer SEKAB*" (Wikipedia 2014-06-14).
[4] Tax breaks used during any part of the years 2000-2012 to promote the holding of green cars that can use biofuels or electricity (SOU 2013:84, 2013).

regardless of fuel consumption. For electric hybrids and gas-fuelled cars the reduction of tax was 40%, for ethanol-fuelled cars 20% (SOU, 2013:84; Kågeson, 2013).

- The green car premium, addressed to private car buyers 2007-2009, with 10,000 SEK.
- Reduced value of fringe benefits for ethanol 2002-2011. Beneficiaries receive a maximum 8,000 SEK reduction/year.
- Reduced value of fringe benefits for biogas 2002–present. The beneficiary receives a maximum 16,000 SEK reduction/year.
- Relief from congestion charges in Stockholm, addressed to owners of gas and ethanol cars 2007-2012. Value up to about 10,000 SEK/year.
- Since 2009, all new 'environment cars' are exempt from annual vehicle tax for the first five years after registration. Reduced vehicle tax for gas and ethanol buses addressed to all owners, with about 20,000 SEK.
- Reduced vehicle tax for cars that can use E85 or biogas addressed to all owners, to 10 SEK/g CO_2 for emissions over 120 g/km, instead of 20 SEK/g.

Instruments with the primary intent not to increase energy efficiency or reduce carbon footprint still influence energy consumption of passenger cars, as well as their emissions. Such examples are parking fees and congestion charges on local and regional level (SOU, 2013:84, 2013). According to SOU (2013:84), the government's monitoring of these instruments has been limited and incomplete.

According to Kågeson (2013), consumer preferences in choice of new car models in Sweden have been strongly influenced by these policy measures. The benefits and subsidies for 'environment cars' under these definitions include free parking in many cities, as well as exemption from the congestion charge in Stockholm for those able to use E85 or biogas until 2012, without consideration of fuel consumption per kilometre.

According to SOU 2013:84 (2013), the effectiveness of the above-mentioned Swedish tax policy effort in supporting the purchase of more fuel-efficient cars is due to some of the frameworks being counterproductively designed. The most serious deficiency is argued to be the absence of incentives to make ethanol- and gas-fuelled cars fuel-efficient.

These vehicles were until 2012 counted as 'environment cars', virtually regardless of their fuel consumption. This meant that the average fuel consumption was higher for a new ethanol car than for a petrol-fuelled car, and that some gas cars had on average higher emissions per kilometre than the same car model which could only run on petrol, mainly due to higher vehicle weight. The subsidies can be said to have focused on fuel shift rather than on increased fuel efficiency.

Other disadvantages in terms of rebound effects are that the design of the benefits in kind has counteracted efforts to reduce consumption by providing favourable conditions for large thirsty cars and has stimulated increased car ownership overall. One more rebound effect that can be identified is the exemption of a low share of biofuels in fossil fuels, which contributes to lower petrol and diesel prices, which can be expected to lead to higher total consumption of fuels.

All these subsidies have resulted in a steady increase in the market share of 'environment cars', from 3% in 2004 to 40% in 2011, among new car registrations. Kågeson (2013) points out that these subsidies have resulted in reduced fuel consumption per kilometre. This in turn means lower costs for driving and thus results in additional mileage as a direct rebound effect.

A bonus-malus scheme to ensure that a larger part of Swedish car sales consists of vehicles that are fuel-efficient is now being discussed for the Swedish car market (SOU, 2013:84, 2013). It means a subsidy for the purchase of fuel-efficient vehicles (bonus), while the purchase of inefficient vehicles is 'punished' with an extra charge (malus). Such schemes have generally been used to incentivise the purchase of energy-efficient products. One such scheme aimed to encourage a transition towards vehicles with lower CO_2 emissions has been successful for this purpose in France, where it was introduced in 2008[5]. As it did not seek to limit total distance travelled, it brought rebound effects as drivers compensated for the savings in fuel costs provided by more fuel-efficient vehicles by driving more. An evaluation from a purely environmental perspective concluded that the scheme included a rebound effect of 20% (equivalent to the price elasticity of driving, per kilometre). Thus, it seems that the overall effect of the policy was zero in terms of vehicle-kilometres driven.

The conclusion from this experience is that a bonus-malus scheme should be designed to focus on incentivising reduced consumption in order to mitigate the rebound effect (European Commission DG ENV, 2011).

In comparison, there have been very few initiatives to decrease emissions from freight transports and OECD have recently identified that such measures are needed for the Swedish freight sector (OECD and Miljödepartementet, 2014).

1.6 What do we mean by rebound effect?

Authors: Anna Mellin & Joanna Dickinson

In the analysis of different policy measures aimed at improving the energy efficiency of the transport sector, an important factor is the total effect on energy demand. When energy efficiency is improved, it is not certain that this will lead to lower overall energy demand or at least lower energy demand than unchanged use of the service or goods would yield (i.e. a ceteris paribus situation). This is due to what the literature calls the rebound effect.

In the context of transport, the rebound effect can be described as when a vehicle becomes more energy-efficient, so less energy should be needed to drive the same amount of kilometres, everything else being constant. However, this is normally not the case. Higher energy efficiency means a lower cost per kilometre driven and this normally leads to increased demand and more kilometres driven, hence generating an increased energy demand – a rebound effect.

The rebound effect was addressed already in 1865, when Jevons reported an increase in coal consumption even though technological improvements had made coal use more efficient. This has since been named the Jevons paradox (Winebrake et al., 2012). The paradox was empirically studied in the 1980s, and was often referred to as the Khazzoom-

[5] The French bonus-malus ranged from a subsidy of €5,000 for vehicles emitting less than 60g CO2/km to a penalty of €2,600 for vehicles emitting more than 260 g CO2/km. Vehicles emitting between 131 and 160g CO2/km received neither a bonus nor a malus. In addition, a "super-bonus" of €300 was given on top of the normal bonus for the purchase of a vehicle emitting less than 130 g CO2/km when proof was given that a vehicle older than 15 years was taken out of service (European Commission DG ENV, 2011).

Brookes postulate[6]. In the more recent literature this phenomenon has been labelled the rebound effect and is defined as "*the difference between the projected energy savings and the actual energy savings resulting from the increased energy efficiency*" (Matos and Silva, 2011: 2834).

For example, if a 10% improvement in engine efficiency results in a 4% drop in fuel use, the rebound effect is 60%, since (10-4)/10 = 0.6 = 60% (Nadel, 2012).

In cases where improved energy efficiency generates an increased total energy demand, this is labelled backfire (Winebrake et al., 2012).

Furthermore, a distinction is generally made between different rebound effects, mainly between *direct*, *indirect* and *economy-wide* rebound effects (UKERC, 2007; Sorrell et al., 2009; Matos and Silva, 2011; Michaels, 2012; Winebrake et al., 2012).

The *direct rebound effect* can be defined as the reaction by individuals or firms to improved energy efficiency. Michaels (2012) provides the comprehensive definition that direct rebound effects are adjustments in the production or consumption of a good whose energy efficiency has increased, which is in line with the definition by Nadel (2012) of the direct rebound effect as the impact of a purchase of an efficient product caused by the purchaser's increased use of that product. In the transport sector, e.g. for a trucking company, this could be the increase in vehicle-kilometres driven after improved fuel efficiency in the vehicles used. Another example is an individual's choice to increase driving when driving costs decrease due to efficiency improvements in passenger cars. Increased petrol use as a result of a lower per-kilometre cost of driving from improved fuel efficiency in cars is often referred to in the literature as a typical example of the direct rebound effect (Small and Van Dender, 2007; IEA, 2012; Michaels, 2012; Chitnis et al., 2013).

The indirect rebound effect is defined as the impact of consumers or businesses re-spending the money saved due to improved energy efficiency by investing in other goods or services related to that improved (IEA, 2012; Nadel, 2012; Chitnis et al., 2013). The indirect rebound effect can thus be defined as the effect of improved energy efficiency in one product or service on other related products or services. For individual consumers, this means for example that money saved from lower energy costs is spent on related other goods or services which can be either more or less energy-consuming. According to Michaels (2012), an example from the transport sector of an indirect rebound effect is if increased fuel economy in cars leads to more driving, also indirectly increasing the demand for tyres. The resulting increase in the tyre industry's energy use would be an indirect rebound effect. Michaels (2012) argues that ultimately all economic sectors are related, but the indirect rebound effect generally refers to close substitutes or complements, and to inputs into production of the sector's good or service.

Economy-wide rebound effects are described as the impact on the rest of the economy of an efficiency improvement in the considered market (in our case transport) (Michaels, 2012). That author argue that effects of energy efficiency policies (e.g. new standards for widely used electric motors) can spill out over the wider economy and generate rebound effects in other parts of the economy than that directly addressed by the actual

[6] Reference for the researchers idea: http://www.jstor.org/discover/10.2307/41322471?uid=366138691&uid=3738984&uid=2129&uid=2&uid=70&uid=3&uid=366138621&uid=67&uid=62&sid=21103310811941

policy. Freed financial resources arising from lower costs for transport when vehicles become more energy-efficient can be used for increased consumption in other areas.

Michaels (2012) provides the example that an increased amount of long holiday flights leads to increased energy consumption for hotels to meet increased demand for rooms and services; for hotel furniture manufacturers to meet increased demand etc. The improved energy efficiency thus produces an ‘income effect’, freeing consumption space and allowing for increased consumption of goods and services with a given income. This may consume additional energy and further increase energy use (Michaels, 2012). Chakravarty et al. (2013) define the economy-wide rebound effect as reductions in the price of intermediate and final goods throughout the economy as a consequence of real price falls in energy services. Such price falls may lead to a series of price and quantity adjustments with energy-intensive goods.

Michaels (2012) argues there is a fourth type of rebound effect, *embedded energy inputs*. This is described as the energy spent in the process of creating more energy-efficient goods – when their manufacture and installation also require energy inputs that must be accounted for. An example from the transport sector is increased energy consumption associated with the production of vehicles with less energy consumption in the operational phase of their lifecycle.

For individuals or households, there is a discussion on income and the substitution effects (into which both the direct and indirect rebound effects could be divided). The substitution effect of a lower price for a good or service due to increased energy efficiency leads to a shift towards more consumption of this specific good or service at the expense of other goods and services. This effect occurs since there is a change in the relative price difference. The income effect reflects that a lower price gives the individual a greater real income and hence the possibility to consume more within the same budget constraints (Berkhout et al, 2000; Sanne, 2006; Broberg, 2011). Greening et al. (2000) notes that in empirical data, it is difficult to separate these two effects from each other. Michaels (2012) concludes that available estimates do not support claims that economic growth per capita would eventually lead to the demand for energy-consuming products and services being saturated, and thus make rebound effects less significant. On the contrary, available research indicates that economic savings resulting from increased efficiency induce more spending on services, such as travel, as well as higher quality goods associated with indirect energy consumption. Michaels (2012) argues that the more complex the economy and the longer the time that can elapse, the greater the rebound effects following improvements in energy efficiency.

In the rebound effect literature, a distinction is often made between short run and long run rebound effects. The reason is that the time rate for which adaptions to price changes occur differs. The short-run rebound effect captures the impact within about a year or so. Such rebound effects are change of vehicle or destination. Long-run rebound effects show how fuel prices affect travel behaviour over a longer period, by turnover of the vehicle fleet and by influencing planning and decisions regarding infrastructure investments, as well as location of housing and workplaces (Litman, 2012a).

1.7 How do we estimate the rebound effect

Authors: Joanna Dickinson & Anna Mellin

In the literature, the main discussion among researchers revolves around the size of the rebound effect and how to measure it properly (Greening et al., 2000; Binswinger, 2001; Matos and Silva, 2011; Chakravarty et al., 2013).

The direct rebound effects of energy use can be measured in various ways (Greening et al., 2000; Frondel and Vance., 2009; Broberg, 2011). The direct rebound effects of personal transportation may, according to Greening et al (2000), be evidenced in three ways – by an increase in the number of vehicles, by an increase in fuel consumption, and by increased vehicle mileage travelled. Broberg (2011) concluded that the direct rebound effects can be empirically measured by analysis of primary data from efficiency experiments.

1.7.1 Elasticities

Direct rebound effects can also be derived by econometric analysis of datasets, and expressed as price elasticity (UKERC, 2007; Frondel and Vance., 2009; Broberg, 2011). Elasticity is a common measure in economics to describe how the demand for a good or service responds to a change in its price. Elasticity is expressed as the percentage change in one variable, for example vehicle travel, caused by a %age change in another, for example fuel price, while holding other measured variables constant (Sorrell et al., 2009; Litman, 2012a). Normally the elasticity is a negative number, i.e. demand decreases as the price increases. Price elasticity models can be used to predict the effects of price changes on travel behaviour (Litman, 2012a).

If price increases by 1% and demand changes by less than 1%, the good or service is said to have inelastic demand (or low price elasticity/sensitivity, or as being inelastic). One reason for this can be a lack of viable alternatives. If price elasticity is low, the degree to which price affects travel activity is low, and the same applies for the rebound effect. In cases of lower price elasticity, increased fuel efficiency in vehicles can be effective (Litman, 2012a).

Conversely, a smaller change in price that leads to a fairly significant change in the demand shows that the demand is elastic. For higher price elasticity (i.e. elasticity greater than 1), the inverse relationship thus applies for increased fuel efficiency in vehicles. It will be a more effective measure leading to a change in travel behaviour, as there will be a higher propensity to respond to the price change by modifying demand. However, the rebound effects are also larger with higher elasticity (Litman, 2012a).

In the econometric approach to rebound effect estimation, energy efficiency is modelled as a price change, so that the price elasticity of demand for energy services or energy can be calculated and used as an approximation of the direct rebound effect.

In the absence of a rebound effect, an elasticity of energy demand with respect to energy efficiency would equal -1, i.e. if the energy efficiency improved by 10%, the demand for energy would be reduced by 10%. The rebound effect is then defined as the difference between the calculated elasticity and the so-called unitary elasticity (i.e. -1) (Winebrake et al, 2012). The more elastic the demand for the actual service, the greater the rebound effect from measures and programmes increasing its energy efficiency (Michaels, 2012). This is also known as own-price elasticity Frondel et al. (2012). There is also cross-price elasticity which can be relevant when talking about rebound effects (Sorrell et al., 2009). Cross-price elasticity captures the effect on one good or service due to a change in the price of another, e.g. how lower travel cost for cars influences public transport demand (Winebrake et al., 2012).

1.7.2 Data sources for estimations

Data sources used for the econometric analysis can be of different types. Cross-sectional, time-series and panel data are potential data sources. These can also be applied to different levels of aggregation – for example household, region or country level. Broberg (2011) illustrate e.g. various methods used that are applicable to various types of data – time series of energy or travel data or panel data aggregated to national or regional (state) level, micro-data from surveys of travel habits that can be cross-sectional or panel data, and aggregated time series of household expenditure (national accounts).

1.7.3 Common assumptions and examples

Linn (2013) pointed out that studies attempting to estimate the rebound effect of increased fuel efficiency in passenger car transport often make at least one of three assumptions: (a) fuel economy is unrelated to other vehicle attributes that may affect driving; (b) the fuel economy of one vehicle in multi-vehicle households does not affect the vehicle mileage travelled by another vehicle; (c) the effect of petrol prices on vehicle mileage travelled is inversely proportional to the effect of fuel economy on vehicle mileage travelled. Linn (2013) showed that these assumptions influence empirical estimates of the rebound effect. Relaxing these assumptions implies that a 1% increase in the fuel economy of all of a household's vehicles increases vehicle mileage travelled by 0.2-0.4% – thus the rebound effect eats up about one-third of the fuel savings that better fuel economy in vehicles would otherwise give. In line with these findings about direct rebound effect estimates, Litman (2012b) concluded from a review of rebound effect studies that typically about one-third of fuel or time savings is used for additional vehicle travel.

As fuel price has traditionally comprised a small proportion of the total costs for passenger vehicles (such as insurance, financing, parking, depreciation etc.), and also in comparison to travel time costs, motorists have generally been relatively insensitive to typical fuel price changes. Thus, vehicle fuel has a low elasticity below 1.0 and is regarded as an 'inelastic good' (Litman, 2012a). However, the long-run elasticity of vehicle travel with respect to total vehicle costs is considered to exceed 1.0 and to be elastic overall, with fuel price elasticity representing a subset of this elasticity.

According to Sorrell et al. (2009), estimates of the direct rebound effect for passenger transport most often measure the energy service in terms of vehicle-kilometres travelled, with energy efficiency defined as vehicle kilometres per litre of fuel. Rebound effects are calculated as any increase in distance driven that were caused by energy efficiency improvements. However, Sorrell et al. (2009) argued that this overlooks any corresponding changes in mean vehicle size and weight and also potential decreases in car occupancy (load factor). They concluded that if energy efficiency was measured instead as tonne-kilometres per litre of fuel, rebound effects could turn up as an increase in driven tonne-kilometres. . From this measure, changes in number of vehicles, mean vehicle weight and mean distance travelled per vehicle and year could potentially be derived. The metric tonne-kilometres is however mainly used in freight transport, rather than for passenger transport.

Michaels (2012) considered rebound effects to be generally difficult to quantify, arguing that indirect effects are usually harder to measure than direct effects because they involve estimates of relationships between different types of goods — for example, how closely consumers view two goods as substitutes. Broberg (2011) also regarded it as difficult to measure rebound effects, because they may evolve over time. This is because it usually takes a long time for people to change their consumption behaviour and for producers to react to these changes by developing new products. It may therefore take some time before the full rebound effect appears and if the rebound effect is studied for a short period of time, there is a risk of underestimating it. Broberg (2011) pointed out that the rebound effect is also influenced by many other factors, which also affect the demand for the commodity or service that consumes energy – factors such as fuel prices and income levels. These factors must be taken into account in statistical analysis to provide accurate estimates of the rebound effect.

1.7.4 Bias in estimations and interpretation of rebound effect

The UKERC report (2007) pointed out that there are a number of potential sources of bias in econometric estimates of the direct rebound effect. Several of these can lead to overestimations of the rebound effect. The most important include input costs, asymmetry, endogeneity and time costs. *Input costs* mean that higher energy efficiency may require new equipment with higher capital costs, and thus estimates of the direct rebound effect that do not consider these could overestimate the effect. (Input costs as referred to by the report UKERC (2007) seems to correspond to the *embedded energy inputs* described by Michaels (2012) as a fourth type of rebound effect, exemplified by manufacture and installation of more energy-efficient goods requiring energy input.)

The UKERC report (2007) further noted that estimates of the direct rebound effect relying primarily on variations in energy prices could result in overestimation, as there is usually an *asymmetry* between higher energy price elasticity for periods with rising prices compared with periods with falling prices. This asymmetry needs to be taken into consideration when calculating the rebound effect. *Endogeneity* means that the relevant variables (energy efficiency and increased demand of transport) are in part determined by each other, and this should be addressed empirically through the use of simultaneous equation models and related techniques, to avoid biased estimates of the rebound effect. *Time costs* are conventionally measured by hourly wage rates, which have historically increased relative to energy prices, and estimates of the direct rebound effect need to control for increases in income in order not to overestimate the direct rebound effect.

Litman (2012a) identified several factors that deserve consideration in future research about rebound effects in the transport sector and their estimation. Firstly, that author claims that the way consumers respond to higher prices needs to be studied in a more disaggregated way. Such analyses should include changes in vehicle travel speed, vehicle mileage, fleet fuel economy, and location decisions. Furthermore, according to Litman (2012a) there is a need to study how price elasticity depends on pricing type and method and how it varies between different periods, with special focus on the fact that there seems to be a trend of increasing elasticity in the past decade. The transferability of fuel price elasticity to other types of transport pricing (such as road, parking and insurance) should also be studied, as should the influence on price elasticity of various factors including demographics, the magnitude of fuel prices relative to household incomes, the magnitude and duration of price changes, price sensitivity variation between urban, suburban and rural areas, and the quality of alternatives and of information about them.

1.8 Rebound effects as a consequence of human behaviour

Author: Mattias Viklund

Rebound effects are, ultimately, a consequence of human behaviour. It is essential to reflect on the possible causes of human behaviour in this context, for at least two reasons. First, rebound effects arise in situations where consumers most likely have (more or less) pro-environmental attitudes, and want to engage in pro-environmental behaviour. Second, consumers are also offered financial incentives to take pro-environmental action.

Attitude is often assumed to be a predictor of behaviour (Eagly and Chaiken, 1998). A positive attitude towards something would then result in a behaviour in line with that attitude, at least when the attitude is specific rather than general, but the strength of the correlation varies among studies. Viklund (2004), for example, found that the relationship between positive attitudes towards electricity saving and self-reported electricity-saving behaviour was quite weak, and that levels of electricity saving instead were more affected by circumstances of living (e.g. type of housing). Previous research (e.g. Andersson, 1994) also suggests that the price of electricity is an important predictor of energy consumption. Viklund (2004) concluded that it is rare to account for a large proportion of variance in behaviour by only using attitudes or similar constructs (e.g. beliefs or values) and that efforts to promote pro-environmental behaviour most likely would benefit from offering financial incentives. In cases of rebound effects, it can be observed that financial incentives are indeed important in order to affect human behaviour, even to the extent that they cause consumers with pro-environmental attitudes to act in a manner that is ultimately harmful to the environment. The challenge, it seems, is to benefit from the power of financial incentives (e.g. subsidies), but not to the extent that the relationship between pro-environmental attitudes and behaviour disappears or becomes inverted.

Even though more practical circumstances, and financial incentives, are important in explaining pro-environmental behaviour, this does not mean that psychological factors are unimportant. Previous research suggests several possible psychological mechanisms underlying pro-environmental behaviour. For example, Cialdini (1993) found that a sense of commitment seems to have an impact on people’s energy-saving behaviour, while a study by Pallak et al. (1980) indicated that the relationship between public commitment and levels of energy consumption lasted throughout a 12-month period, hence public commitment could have more than short-term effects.

Axelrod and Lehman (1993) developed a multivariate model that accounted for 49% of the variance in environmentally concerned behaviour and which included six factors: principled outcome desires (the extent to which respondents act in accordance with deeply held values for the environment), issue importance (absolute importance of the environment to the individual and its relative importance in comparison with other social concerns), self-efficacy (respondents’ beliefs that they, personally, have the capability to engage in actions that can help solve environmental problems), social outcome desires (the extent to which family, friends and the community serve as guides to one’s behaviour with respect to the environment), channel efficacy (perceived difficulty the individual expected to encounter when attempting to act in environmentally friendly ways), and threat perception (perceived likelihood, severity and immediacy of environmental problems).

Research on the reasons for a gap between attitudes and behaviour could help to explain rebound effects. Sadalla and Krull (1995) investigated possible psychological barriers to energy conservation, based on the hypothesis that conservation measures could negatively affect a person by stigmatising the individual and reducing his or her status. The assumption was to some degree supported by the data and led to the conclusion that since consumption seems to be equated with status, it might be easier to promote the consumption of products that conserve energy than to discourage energy consuming behaviour. It should be added, however, that it is reasonable to assume that the concept of status is to some degree culturally dependent and also varies over time.

One interesting concept that has received attention as a possible explanation for the gap between attitudes and behaviour is that of habit. Simply put, old habits could be the reason for the limited change in environmental behaviour despite pro-environmental attitudes. However, in the case of rebound effects, it could be argued that habits have actually changed, or that new habits have been created as a consequence of financial incentives. Henriksson (2008) argued that travel patterns of urban dwellers can be made environmentally sustainable in the long term, based on the premise that habits have an inherent resistance to change. This, in turn, Henriksson argues, should lead policy makers to the conclusion that habits create opportunities rather than obstacles to sustainable development.

In an extensive study, Goodwin and Lyons (2010) reviewed research on public attitudes to transport. On a conceptual level, they concluded that previous research has largely focused on public attitudes to transport as a complex psychological phenomenon, with highly contested theoretical arguments about how they emerge and change, subtle distinctions derived from the way they are expressed, and especially their relationship with behaviour. There are, according to Goodwin and Lyons, strong arguments that attitudes both precede and follow choice, with elaborate structures connecting values, attitudes, intentions and action with constructs (especially cognitive dissonance) of the way in which actions may be ill-matched. Simply put, research on psychological mechanisms underlying environmental attitudes and behaviour is a complex endeavour.

Interestingly, Goodwin and Lyons also found evidence for a rather strong willingness to change behaviour towards more pro-environmental action, but they noted that it is not clear how the standpoint ‘ready to consider changing’ converts to the behaviour ‘changing’, for which research on actual choices is probably more important than research on attitudes.

A recent report by the International Risk Governance Council (IRGC, 2013), reviewing literature on the rebound effect from a consumer perspective, makes an important distinction between the effects of environmental attitudes on indirect versus direct rebound effects. Environmental consciousness may prevent people from overconsumption and steer their investments towards low emission goods and services (thereby avoiding indirect rebound effects), but it might be more difficult to avoid direct rebound effects even when consumers have pro-environmental attitudes.

The report also suggests that to fully understand consumer responses to changes in energy efficiency and energy prices, and thereby gain an understanding of rebound effects at a consumer level, it is important to take into account a number of aspects – not only perception of prices, attitudes and values, but also factors such as prestige, level of knowledge in the application of energy-efficient devices, lifestyles, social and personal norms, habits and time spent on energy-consuming activities.

To sum up, it seems clear, in particular in a Swedish context where little research has been done on the subject, that there is a great need for more research in order to understand how economics and psychological theories could be combined to avoid or mitigate rebound effects.

2 Methods

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The starting point for the literature review was the division of policy measures in the transport sector to achieve energy efficiency, and also the goal of reduced climate impact. Policy measures for achieving more energy-efficient passenger and freight transport can be divided into three categories (Johansson et al., 2012):

- Increased energy efficiency in vehicles.

- Increased use of more energy-efficient fuels.

- Changed community planning that can contribute to reduced transport demand, as well as a modal shift towards increased traveling and transport with more energy-efficient transport modes.

A report by Broberg (2011) was used initially to find suitable references.

In the work we sought to identify measures and management controls in the transport sector carried out with the intent (partly or entirely) of achieving more energy-efficient transport and movement. For each provision and management control measure analysed, we endeavoured to identify its purpose and relate the rebound effect to the stated purpose.

We included provisions and management control measures aimed at reducing greenhouse gas (GHG) emissions by reducing commuter traffic and reducing fossil fuels in the transport sector, as these lead to energy efficiency. Provisions and management control measures not put in place to achieve energy efficiency, reduce commuter traffic or reduce emissions of GHG were not included, since it is more complicated to deduce their potential rebound effects.

Conducting this study on rebound effects proved to be quite complex as in many papers this phrase was not included. Search words such as "increase in traffic", "increase in car travel", "traffic", "car passengers", "bike riding", "fuel" etc. resulted in a large number of hits, but the majority lacked relevance with regard to rebound effects. Searches for these kinds of effects which were not described as "rebound effect" therefore had to be conducted through Google, EU databases with "good practice" regarding mobility management such as and recommendations from researchers and government officials. Because it proved difficult to conduct searches, in several instances "grey literature", such as agency reports and governmental investigations were used as a source.

A conventional search in metadata, with hits for search words in titles, abstracts and specified subject words for publications, was carried out in the Scopus database, the TRID database and in National Transport Library Catalogue at VTI. For some search words this did not yield many hits and we checked every hit, e.g. "policy measures". Words with different endings and spellings, e.g. "sustain*", were searched for with wildcards to get as many hits as possible. The search was conducted in Nationell bibliotekskatalog (formerly Trax), located at www.transportportal.se.

The searches were conducted in February 2014 in the following databases, in accordance with Table 3 below:

- National Transport Library Catalogue at VTI - a bibliographical database that covers Swedish transport research www.transportportal.se

- TRID - the world's largest bibliographical database within the area of transport research, which contains commercial scientific publications as well as "grey material" http://trid.trb.org/
- Scopus - a bibliographical database which covers all fields of research. It contains mostly scientific articles http://www.elsevier.com/online-tools/scopus.

Table 3 Search data used in the literature search.

Search phrases	Scopus	TRID	VTI
Rebound effect, Khazzom	TITLE-ABS-KEY(khazzoom AND brooke*) AND PUBYEAR > 1989	keywords containing (khazzoom AND brooke*) OR (jevon* AND paradox*) or "rebound effect*" between dates 2000 – 2014	rekyl# or rebound#
	TITLE-ABS-KEY(jevon* AND paradox*) AND PUBYEAR > 1989		
	TITLE-ABS-KEY("rebound effect*") AND PUBYEAR > 1989)) AND (TITLE-ABS-KEY(transport* OR traffic) AND PUBYEAR > 1989		
	Title-ABS-KEY("down* thomson*") AND PUBYEAR > 1989		
	TITLE-ABS-KEY(energy OR emission OR carbon dioxide OR co2 OR greenhouse OR "fuel consump*" OR environment* OR sustainabilty OR "sustainable develop*") AND PUBYEAR > 1989) AND (TITLE-ABS-KEY(backfire) AND PUBYEAR > 1989)		
Park and Ride		title containing "park and ride" or "fringe parking" between dates 2000 – 2014	(park and ride# or infartspark# or fringe park#) and yr>1999
Elcykelbud	TITLE-ABS-KEY("cargo bike*" OR "cargo bicycl*") AND PUBYEAR > 1999	"cargo bike*" or "cargo bicycl*"	elcyk# or #cykelbud# or electri# two# or cykellev#
	TITLE((bicycl* OR bike* OR cycling) AND (freight OR cargo OR deliver* OR courier)) AND PUBYEAR > 1999	electri* and (bicycl* or bike* or cycling) and (cargo or freight or deliver* or courier) between dates 2000 – 2014	(deliver# OR cargo# OR freight#) AND (#bike# OR #bicycl# OR #cycling#) and elect#

	(TITLE(bicycl* OR bike* OR cycling) AND TITLE-ABS-KEY (freight OR cargo OR deliver* OR courier) AND TITLE-ABS-KEY(electric*)) AND PUBYEAR > 1999		
	TITLE("e-bike*" OR "e-bicycle*") AND PUBYEAR > 1999		
	(TITLE-ABS-KEY("e-bike*" OR "e-bicycle*") AND TITLE-ABS-KEY(deliver* OR cargo OR freight OR courier)) AND PUBYEAR > 1999		
Cykelbanor, busskörfält	(TITLE-ABS-KEY("bus lane*" OR busway OR "bicycle lane" OR "cycle lane" or "cycle track*") AND TITLE-ABS-KEY(capacity OR "level of service" OR "traffic flow" OR "traffic count") AND PUBYEAR > 1989	keywords containing ("bus lane*" or busway* or "bicycle lane*" or "cycle lane*" or "cycle track*") and (capacity or "level of service" or "traffic flow*" or "traffic count*") between dates 2000 – 2014	(busskörfäl# or bus lane# OR busway# OR bicycle lane# OR cycle lane# or cykelfält# or #trafiksepar# or traffic separat#) and yr>1999
		title containing "bus lane*" or busway* or "bicycle lane*" or "cycle lane*" or "cycle track*") and with indexterms containing traffic or "level of service" or capacity	(cycle track# or cykelban#) and #separat# and yr>1999
		title containing "bus lane*" or busway* or "bicycle lane*" or "cycle lane*" between dates 2000 – 2014	
Mobility Management		title containing tdm or "transport demand management" or "mobility management" between dates 2000 - 2014	mobility management and yr>1999
			(kollektivtrafik# OR public transport# OR transit) and (campaign# OR #kampanj# OR increas# OR ökat resa# OR publicity OR mark-nadsför# OR marketing# OR advertis# OR #åtgärd# OR aktioner#) and (car OR cars OR bil OR bilar# OR bilen# OR bilres# OR private trans-port# OR automobi# OR bilåk# or privatbil# OR bilism#) and yr>1999

A search of literature on **artificial lighting** was performed by combining the words Lighting + rebound + effects in Scopus on 27 May 2014. A total of 23 papers were found and a search for similar words was then performed in Google.

Scopus was used for a literature search on 27 May 2014 on **waterborne transport** by combining the terms "shipping/sea transport/ferry/waterborne + rebound effects. An additional search was then conducted in Google and Google Scholar.

The search for rebound effects and **human behaviour** were conducted in May 2014 by using a combination of three groups:

1) Gasoline/petrol prices, subsidies, tolls, congestion charges, politics, taxes, instruments, parking fees, incentive, road pricing, congestion charging, politics, policy, taxes, taxation, subsidy, fuel price.
2) Emission, environment, sustainability, pollution, climate, greenhouse, carbon dioxide, CO2, eco, emissions, climate, greenhouse effect, greenhouse gases, CO_2.
3) Driving, driving, journey, transport mode, traffic, travel, commuter, behaviour, attitude, choice, transportation mode, vehicle ownership, psychology, psychological, interview, questionnaire, social, sociology, behaviour, attitudes, transportation, travel patterns, travel choices, carless, carfree.

The search were conducted in Scopus and in the Nationell bibliotekskatalog (formerly Trax) located at www.transportportalen.se.

3 Passenger transport on road and rail

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In the transport sector, energy consumption is related to and can be calculated based on the amount of passenger and freight transport. The amount of transport is generally expressed in terms of vehicle-kilometres, passenger-kilometres or tonne-kilometres. One measure of transport is the total number of kilometres that a number of vehicles move (vehicle-kilometres). The corresponding measure for passenger traffic is passenger-kilometres, i.e. the transport of one person one kilometre. Freight transport is measured by the weight of goods carried a certain distance, usually expressed in tonne-kilometres, where a tonne-kilometre is equivalent to one tonne transported one kilometre.

Litman (2012a) pointed out that rebound effects connected to increased vehicle travel generally occur as a result of increased fuel efficiency, cheaper fuels or increased road capacity contributing to increased traffic speeds.

Broberg (2011) concluded that the fuel and energy consumption from road transport consists of three parts and that rebound effects can arise from each of these three aspects:

- The size of the vehicle fleet.
- The number of vehicle kilometres travelled by each vehicle.
- Fuel consumption per kilometre.

Rebound effects in passenger cars are explored further in the following sections. There are also potential secondary or indirect effects of increased energy efficiency in the transport sector (see Chapter 9).

A number of reviews have been conducted on direct rebound effects of passenger cars (Table 4) and are examined in the following sections.

Table 4 Summary of reviews of rebound effects.

Survey	Data source	Rebound estimate interval	
		'Short-run'	'Long-run'
Small and Van Dender (2007)	Cross-sectional time-series data of US states, 1966-2001	4.5%	22.2%
- " -	As above, and assuming income and starting fuel efficiency to be at 1997-2001 levels	3.1%	15.3%
Chakravarty et al. (2013)	USA	3-22%	5-30%
	Western European countries	36.4%	39-105%
Ajanovic et al. (2012)	Data from EU-15 countries 1970-2007		48% from increasing use of more comfortable cars; 22% from increased vehicle mileage
Ajanovic and Haas (2012)	Applied co-integration analyses to six European countries and their aggregate over the period 1970-2007. The analyses considered the impact of fuel prices, household income and fuel intensity on fuel consumption.		The calculated rebound effect due to lower fuel intensity and due to the switch to diesel is calculated to be 44% more kilometres driven if fuel intensity is improved 100%.
UKERC (2007)	17 econometric studies of the rebound effect in passenger car transport in OECD countries.	4.5-87% in US-based studies.	Range of values, 3-87% "Best guess", 10-30%.

Sorrell et al. (2009)	Review of 7 studies covering econometric estimates of the direct rebound effect for personal automotive transport using aggregate time-series or cross-sectional data.		Long-run estimates of the rebound effect for car travel with respect to cost of energy (most cases) to be within the interval of 10-30%.
Binswanger (2001)	Using regression models on empirical estimates of the rebound effect in 9 covered studies, mainly based on data on vehicle miles travelled between the 1960s to the 1980s, on state level and national level in USA.		5-30%.
Greening et al. (2000)	22 studies including both studies based on empirical time series of national or state-level data, as well as econometric studies on petrol demand, mostly covering the USA but also a few surveys covering other countries		10-30% based on a 10% increase in fuel consumption
Hymel et al. (2010)	Cross-sectional time series data at the level of US states for 1966 through 2004.	4.7%	24.1%
NHTSA (2011)	Studies based on time series data from the 1950-1990s, as well as recent studies based on data from the last decade.		16-30%, towards 2030 4-16% – 10% suggested as reasonable compromise estimate.
Frondel et al. (2012)	Panel estimation and quantile regression analysis based on household travel diary data from the German Mobility Panel 1997-2009		An average rebound effect in the range 57-62%.
Frondel and Vance (2013)	Panel estimation methods and household travel diary data covering 1997-2009		A rebound estimate for German single-vehicle households in the range 46-70%.
Broberg (2011)	Several literature overviews and studies covering price elasticity for petrol demand, based on general equilibrium models (CGE models)		Based on petrol and diesel demand price elasticity, a rebound effect in the transport sector from increased fuel efficiency in transport in the range 10-70% for a Swedish context.

3.1 Estimates of the direct rebound effect associated with more fuel-efficient passenger cars

A common example of rebound effect in the transport sector is when increased fuel efficiency in cars leads to lower driving costs. According to Broberg (2011) and Sorrell et al. (2009), energy consumption in passenger transport by car is the field that has been covered to the greatest extent in the research on rebound effects. Much research has been carried out to estimate the direct rebound effect from increased fuel efficiency in vehicles, based both on empirical data and model-based analyses. Increased energy efficiency in passenger car transport is, according to Sorrell et al. (2009), the only area where the evidence is sufficiently strong to allow the magnitude of the direct rebound effect to be quantified with some confidence.

The most common perspective in existing estimates of the rebound effect for passenger cars is, according to Sorrell et al. (2009), how a price change for the travel cost, due to e.g. improved fuel efficiency or technological efficiency, changes the demand for the service or energy use.

3.1.1 Different estimates of direct rebound effects from more fuel-efficient cars based on US and OECD data

A study extensively referred to in the literature about the rebound effect (among others Sorrell et al., 2009; NHTSA, 2011) was conducted by Small et al. (2007). It estimated the rebound effect of increased fuel efficiency in motor vehicles. In the study, cross-sectional time-series data for US states 1966-2001 was used together with a model accounting for endogenous changes in fuel efficiency and allowing the rebound effect to vary with income, urbanisation and fuel cost of driving. The resulting estimates of the short-run and long-run rebound effect were 4.5% and 22.2%, respectively. With income and starting fuel efficiency at 1997-2001 levels, the study indicates rebound effects varying between 3.1% in the short run and 15.3% in the long run.

Chakravarty et al. (2013) made an overview of empirical estimates of rebound effects from increased fuel efficiency in the transport sector, noting that in developing countries it is found to vary between no rebound at all to backfire. In developed countries, a 105% long-run rebound effect was found in the UK. Direct rebound effects for passenger car transport in the USA on national level, as well as Florida and Hawaii on state level, were found to lie in the interval 3-22% in the short run and 5-30% in the long run. For countries in Western Europe (UK, France, Italy, Portugal and Germany), the short-run rebound was found to be 36.4%, and the long-run rebound between 39-105% (thus, even backfire occurs). The survey also showed that the long-run rebound effects are estimated to be larger than the short-run effects.

Ajanovic et al. (2012) analysed the impact of changes in fuel intensity[7] and car size on fuel demand for passenger cars, considering both long-term average engine power of cars and short-term vehicle-kilometres driven. The analysis was based on data from EU-15 countries, from 1970 through 2007. The effect of the energy price on energy consumption was calculated, as well as the impact of vehicle mileage driven and the increase in average car power (kW) explicitly. The results showed that improvements achieved in fuel efficiency in the car stock in EU-15 countries have not led to the theoretically calculated energy savings. The reason is that the improvements have been counterbalanced by changes in consumer preferences towards more comfortable cars, as well as increased driving distances.

Ajanovic and Haas (2012) examined the impact of changes in fuel prices, household income and fuel intensity on total fuel consumption and the demand for vehicle-kilometres driven in car passenger transport by co-integration analyses based on aggregated data from six European countries 1970-2007. The analyses also covered how changes in fuel prices and fuel intensity interact. The calculated rebound effect due to lower fuel intensity and due to a switch to diesel was calculated to be 44% more kilometres driven when fuel intensity was improved by 100%.

Based on a survey of 17 econometric studies of the rebound effect in passenger car transport in OECD countries, Sorrell et al. (2007) found that studies using aggregate time-series and cross-sectional data suggests that the long-run direct rebound effect for

[7] i.e. litres of fuel used per 100 kilometres.

personal automotive transport is between 5% and 30%. However, these estimates are based on too limited data to be considered fully reliable. Estimates of the direct rebound effect based on aggregate panel data are claimed to be more robust, as they are based on greater numbers of observations. Such studies point at a long-run direct rebound effect of 22% for the USA, while studies using disaggregated data sources for the USA provide estimates of up to 87%, although the best quality estimate among these studies is a direct rebound effect of 23%. In the short-run, the rebound effect varies between 4.5 and 87 %. Furthermore, Sorrell et al. (2009) reviewed seven studies covering econometric estimates of the direct rebound effect for personal automotive transport using aggregate time-series or cross-sectional data. They concluded that considering the differences in methodology and data between the different studies covered in the review, these results seem to be relatively robust.

Binswanger (2001) reviewed nine empirical studies of the 1980s and 1990s on rebound effects and found that the rebound effects estimated in these studies varied between 5-30%.

A review of estimates of the direct rebound effects related to increased fuel efficiency in personal transportation was also conducted by Greening et al. (2000), covering 22 studies. The overall conclusion was that the potential size of the rebound effects lies within the interval 10-30% (based on a 10% increase in efficiency of fuel consumption). However, those authors underlined that there is no common definition of the rebound effects and how to measure these, and hence the results vary and are not straightforward to compare.

Hymel et al. (2010) analysed aggregate personal motor vehicle travel considering vehicle travel, fleet size, fuel efficiency and congestion formation. They also measured the impacts of driving costs on congestion, as well as rebound effects affecting motor-vehicle travel (aggregate road capacity causing “induced demand”) and driving costs, including those caused by fuel economy improvements. Cross-sectional time-series data from US states for 1966-2004 were used to estimate the effects. . They found that the average rebound effect across US states and years in the sample, stated as a positive percentage, was an estimated 4.7% in the short run and 24.1% in the long run.

Most of the above empirical studies of the direct rebound effect from increased fuel efficiency in passenger transport are based on data from the USA. Among studies focusing on European data, Matiaske et al. (2012) examined to what extent higher fuel efficiency of cars affects additional travel, and also looked into how additional variables influence this. Matiaske et al. (2012) estimated an unbalanced random effects panel model of the rebound effect, based on two panel waves from the German Socio-Economic Panel (SOEP)[8], 1998 and 2003, in order to take full advantage of the information in the data available, and to avoid problems due to possible selection effects. For vehicles with a consumption of more than approx. 8 litres/100 km, the results indicate that as fuel consumption becomes lower, the distance driven becomes larger.

In addition, the results from Matiaske et al. (2012) show a positive diesel effect – suggesting that owning a diesel engine car is associated with longer distance driven.

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[8] The dataset used to estimate a theoretical model of the rebound effect covers two panel waves, 1998 and 2003, taken from the German Socio-Economic Panel (SOEP). The SOEP is a household panel with annual interviews with about 12,000 households and approximately 24,000 individuals in 2008 (Matiaske et al., 2012).

The study also examined how a selection of variables tends to influence this non-linear rebound effect. The results showed that it is influenced by income, education, travel time to the workplace, household private car use, and owning a season ticket for the public transport system. The results also revealed that private car use is significantly influenced by general emotional attitudes towards car driving and subjective attitudes towards the environment (Matiaske et al., 2012). For example, the number of kilometres driven increases when the household head takes pleasure in car driving and has less concerns about the environmental consequences.

Based on panel estimation methods and household travel diary data covering 1997-2009, Frondel and Vance (2013) estimated the rebound effect for German single-vehicle households to be in the range 46-70%.

Frondel and Vance (2009) quantified the effects of fuel prices and fuel economy by estimating econometric models of car use on a panel of 10 years of travel-diary data collected in Germany between 1997 and 2006[9]. During the study period, real fuel prices in Germany rose by 3% per year.

Frondel et al. (2012) used both panel estimation and quantile regression analysis based on household travel diary data from the German Mobility Panel 1997-2009. The purpose was to examine four varieties of definitions of the rebound effect. The first three are those commonly referred to in the literature when describing the direct rebound effect from increased fuel efficiency in passenger cars: Elasticity with respect to changes in either efficiency (definition 1), service prices (definition 2) or fuel prices (definition 3). The fourth definition is given by the negative of the fuel price elasticity of the demand for transport services. Frondel et al. (2012) showed an average rebound effect in the range 57-62%, but found no effects related to geographical location, income level or the number of cars owned.

NHTSA (2011) presented a summary of historical literature on the rebound effect, based on time-series data from the 1950-1990s, as well as recent studies based on data from the last decade. Changes in fuel prices were taken into account in that analysis of the rebound effect associated with increased fuel efficiency in passenger cars. It was found that studies of the rebound effect based on household surveys display more variability, which could be explained by omitted variable bias due to vehicle age not being included as an explanatory variable, to the average number of vehicles per household differing in the surveys and to this variable having an impact on the rebound effect, or to difficulties in distinguishing the impact of residential density from that of fuel prices.

The results of the analysis by NHTSA (2011) are broadly consistent with the findings from previous research summarised above. The historical average long-run rebound effect is estimated to be in the range 16-30%. NHTSA (2011) reveals an indication that the long-run direct rebound effect is declining in magnitude over time, causing estimated long-run rebound effects in the range 4-16% in 2030.

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[9] The German Mobility Panel (MOP 2007) is an ongoing publicly available travel survey. This survey takes place over a roughly six-week period in each of three consecutive years, when respondents record the price paid for fuel with each visit to the petrol station, distance travelled, and vehicle attributes such as fuel economy and fuel type for each car driven during the survey. The unit of observation in this travel survey data is the car. Households owning multiple cars occupy several rows of data (Frondel and Vance, 2009).

Based on existing research of the rebound effect in the transport sector, NHTSA (2011) concluded that 10% is a reasonable compromise estimate of the magnitude of the rebound, as being a value on the low end of the historical estimates in the literature, which range between 10 and 30 %. It is also at the upper end of the 5-10% range of estimates for the future rebound effect reported in recent studies, as well as being within the 3-16% range of forecasts of the future magnitude of the rebound effect developed by NHTSA itself. This is in line with the UKERC report (2007), who showed a likely direct long-term rebound effect of slightly greater than 10% in the transport sector.

NHTSA (2011) underscored that since there has been little variation in fuel efficiency in the data over time, analysing the impact of increased fuel efficiency based solely on vehicle mileage (VMT) can be difficult when using econometric analysis of historical data. This is stated as the reason why studies of the rebound effect using time-series data often examine the impact of petrol prices on VMT, or the combined impact of both petrol prices and fuel efficiency on VMT. According to NHTSA (2011), it is important to account for the effect of fuel prices when attempting to estimate the rebound effect. Failing to control for changes in fuel prices is likely to bias estimates of the rebound effect. However, there is a risk of exaggerating the potential impact of the rebound effect if people are more responsive to changes in petrol prices than to changes in fuel efficiency itself.

Litman (2012a) discussed the various results found in the literature on the magnitude of the direct rebound effect. Studies carried out based on data from the last quarter of the 1900s showed declining vehicle travel price elasticity that was below -0.1 (a 10% fuel price increase reduced fuel consumption by less than 0.1%) in the short run and -0.2 in the long run. However, these studies covered what can be considered a unique period of increasing travel demand, rising income, automobile-orientated planning and declining inflation-adjusted fuel prices. Hence, findings in recent studies indicate that driving has become more price-sensitive, showing some higher fuel price elasticity based on data after 2000. In fact, more recent estimates on fuel price elasticity are between -0.1 and -0.2 in the short run and between -0.2 and -0.3 in the long run. Litman (2012a) argued that these latter rebound effects represent more normal levels and will probably rise further, should fuel prices continue to increase relative to income.

Few studies from Sweden on the rebound effect were found here. Broberg (2011) refers to several literature reviews and studies covering price elasticity for petrol demand, based on CGE models[10]. In the short term, Broberg (2011) found that the estimated price elasticity for petrol demand is -0.25. In a long term, it is -0.64 on average, and in a Swedish context it is often assumed to be -0.7. For petrol, in studies based on a Swedish context it has been estimated to be -0.49 and for diesel -0.32. The corresponding price elasticity for vehicle-kilometres is -0.29 in the long term and -0.10 in the short term. Thus, according to Broberg (2011), the rebound effect in the transport sector from increased fuel efficiency in transport is within the range 10-70%.

[10] CGE is an abbreviation of ‘computable general equilibrium’. CGE models are tool kits allowing researchers to compare the estimated effects of policies in detail. The model numerically solves a large system of equations that incorporate the determinants of economic choices made by consumers and producers of the economy’s goods and services, based on empirical data and assumptions about economic magnitudes and behaviour. CGE are based on utilitarian maximisation and perfect market assumptions, and not so much empirical evidence (Michaels, 2012). Such models have, according to Broberg (2011), advantages in terms of long-term analyses. Most CGE models use a social optimum equilibrium, where firms and households are assumed to act in an economically rational basis of complete information. This has prompted some criticism that the models disregard existing market imperfections, such as imperfect information, and that econometric models are better suited for analyses of measures aimed at removing such market imperfections.

3.1.2 Different estimates on direct rebound effects from more fuel-efficient cars based on data from developing economies

Looking at studies of the direct rebound effect of increased fuel efficiency in passenger cars in developing economies, the empirical results reveal a direct rebound effect for passenger transport in urban China of about 96% (Wang et al., 2011). That study also showed that the direct rebound effect from passenger urban transport in China varies with household expenditure, and that it would most likely decline with an increase in per capita consumption expenditure (Wang et al., 2011). In the review by Chakravarty et al. (2013), based on empirical studies of the direct rebound effect from increased fuel efficiency in the transport sector of the developing economies of India and China, direct rebound effects were also found to be high, between 96 and 107 %.

Based on a sample of over 100,000 households from the 2009 National Household Travel Survey, Wang and Chang (2012) showed that the rebound effect has been found to be only significant for the lowest income quintile.

Lin and Liu(2013) estimated the rebound effect for more fuel-efficient passenger transportation in China and reported a value of 107%, which actually means a ‘backfire effect’. Wang et al. (2012) examined the direct rebound effect for private passenger transport in Hong Kong by econometric model estimations and found that it varied between 45% in 1993-2009 and 35% in 2002-2009. This indicates a declining trend in the direct rebound effect for passenger transport over time in Hong Kong over the study period.

3.1.3 Summary of estimated direct rebound effects from more fuel-efficient cars

A summary of the reviews reveals great variation in the different estimates in the literature of the direct rebound effect of increased fuel efficiency in passenger cars. This variation depends mainly on the service or product, as well as the country been studied (Broberg, 2011; Chakravarty et al., 2013). Broberg (2011) points out that the many approaches in how the rebound effect has been estimated – with different methods and models, on different economic levels, short run/long run – have contributed to a large spread in the empirical estimates. This spread has contributed to widely different conclusions about the size of the rebound effect. Frondel et al. (2012) pointed out that one major reason for the diverging results of empirical studies trying to estimate the direct rebound effect is that there is no unanimous definition of the concept. However, their review showed that despite the variation in the different estimates, there is clear evidence of direct rebound effects from increased fuel efficiency in cars caused by an increase in the distance driven due to the lower cost of fuel consumption.

3.2 Fuel shift

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Renewable fuels in the transport sector are often seen as a way to reduce the sector’s GHG emissions by reducing the consumption of fossil fuels, but have been criticised since CO_2 emissions from a well-to-wheel perspective are not considered sufficiently thoroughly for renewable fuels. Irrespective of that, renewable fuels may have lower energy density and be less energy-efficient per kilometre than the fuels they replace. This can cause a rebound effect from an energy and fuel consumption perspective.

3.2.1 Ethanol

The energy content of ethanol, a renewable fuel, is 30% lower than that of petrol, which means that a car that runs on E85 has higher fuel consumption (Swedish Energy Agency 2013b). The consumption values quoted in car advertisements are almost always based on petrol. This means that the same car when ethanol fuelled consumes 30% more fuel (Swedish Energy Agency, 2013b).

This indicates that policies aiming to reduce GHG emissions by an increased proportion of vehicle mileage with ethanol-fuelled cars can lead to rebound effects through increased fuel consumption per distance driven. Ethanol has in recent years often had a lower fuel cost per kilometre than petrol, which can also lead to rebound effects by increasing the distance travelled.

3.2.2 Diesel

A special case is the shift from petrol to diesel vehicles in the fleet. Matiaske et al. (2012) found that there is a positive diesel effect connected to rebound effects from increased fuel efficiency in cars, and that the longer the distance driven, the higher degree of diesel engines among the cars used.

Several instruments introduced in Sweden to reduce GHG emissions from transport have focused on promoting a greater proportion of diesel vehicles in the fleet (Kågeson, 2013). Diesel has higher energy content than petrol. This, combined with the higher efficiency of diesel engines than petrol engines, allows diesel cars usually to have lower fuel consumption than petrol cars. However, as diesel fuel contains more carbon per litre than petrol, the carbon emissions per litre of fuel used are higher. To make sure a diesel car has less impact on climate change than a petrol car, measured fuel consumption in litres needs be at least 14% lower (Swedish Energy Agency, 2013b).

Kågeson (2013) studied the increased market share of diesel cars in Sweden, which grew from under 10% in 2005 to 62% in 2011. The main reason for the increase was the introduction of a number of low-consuming diesel car models able to meet a 120g CO_2 threshold for 'environment cars' that cannot use renewable fuels such as ethanol. The exemption from 2009 for all new 'environment cars' from annual vehicle tax for the first five years after registration has led to diesel cars being more subsidised than the corresponding petrol cars. According to SOU (2013:84), diesel cars have lower fuel taxes and higher vehicle allowances have distorted competition with efficient petrol cars to the advantage of diesel cars.

Diesel car models categorised as 'environment cars' increased their share of the diesel car fleet from zero to 41% between 2005 and 2011. According to Kågeson (2013), this 'dieselisation' of the car fleet appears to have had a slight rebound effect caused by increased annual vehicle mileage. As the fuel consumption per kilometre for driving a diesel car is lower than for petrol, Kågeson (2013) pointed out that this leads to lower costs for driving and thus results in additional mileage as a rebound effect. Kågeson (2013) referred to an upper limit for the direct rebound effect of 30%. He based this on international studies including the UKERC report (2007) and Small and Van Dender (2007), which indicate that the fuel elasticity for mileage is about 0.3.

Thus, for Sweden, there is an accompanying rebound effect for shifting fuel to diesel but the exact level has not yet been calculated.

3.2.3 Electric vehicles (EV)

Electric power offers high energy efficiency in vehicles and low emissions if the electricity production is largely based on renewable or carbon-neutral energy. An increased proportion of electrical power in terms of plug-in-hybrids, battery cars and rail is considered to be an important component for reaching the climate goals (Åkerman and Åman 2008).

Steen et al. (2013) showed that electric cars have a slightly greater impact on the environment from the automotive lifecycle than conventional fossil fuel cars, but that the levels depend on several factors. For the production of electric cars (EV) and plug-in hybrids, special metals for batteries and fuel cells are needed (for example lithium, cobalt, nickel and platinum), which are energy-intensive to produce.

Hawkins et al. (2013) showed that whether an electric vehicle has less environmental impact in a lifecycle perspective than a conventionally fossil-fuelled vehicle depends on parameters such as electricity source, use phase energy consumption, vehicle lifetime and battery replacement schedule. Production impacts are more significant for EVs than conventional vehicles (Hawkins et al., 2013). Battery production is energy-consuming and leads to significant emissions of GHG, as well as emissions of carcinogens and contributions to ozone depletion and ecotoxicity (Cooney et al., 2013). Depending on the vehicle lifetime, EV can have the same or even larger impacts from an environmental perspective, including energy use, than a diesel vehicle (Hawkins et al., 2013).

Figenbaum (2013) referred to two studies of the travel habits of electric car owners in Norway. One was a survey of 600 electric car owners and a range of another part of the population, consisting of 600 individuals with a driving licence in three Norwegian cities. The survey showed that electric car owners changed travel habits after having acquired the electric car. They walked, cycled and used public transport less frequently than the control group, and travelled by car significantly more often. These differences were large and statistically significant. The second study, a questionnaire sent to all individuals and businesses registered as the owner of one or more electric cars, showed that electric cars are mostly used for short trips, such as commuting and shopping trips. This seems reasonable given that electric cars today typically have a range of 100-150 kilometres per charge (SOU, 2013:84). For shorter trips, the electric car can thus be a substitute for bicycling, walking or public transport, leading to a rebound effect at the system level when travel modes with lower (or even zero) energy consumption are replaced by battery-driven travelling.

In conclusion, EV can have a substantial environmental impact (and energy consumption), depending on the vehicle lifetime. Furthermore, depending on individual usage, there might be rebound effects on a system level if carbon-free travelling is replaced by increased use of EV.

3.2.4 Electric bicycles and scooters

Electric bicycles (E-bikes) and scooters have recently become more popular, but the effects of this relative new mode of transport, including energy efficiency effects, are quite unknown. Engelmore (2012) addressed the effects of E-bike use on accessibility for commuter traffic in compact Dutch cities and on total energy usage and emissions by analysing different scenarios for commuter traffic to the city of Groningen. One conclusion drawn is that it uncertain whether additional E-bike movements result in less car movements. It is likely that the extra space on the road is filled immediately by new car users or people who used to travel outside rush hour.

When E-bike use increases, Engelmore (2012) showed that the result is a shift of the modal split. Size and cause of the modal shift differ per situation and with the research method applied. The E-bike replaced the conventional bicycle by 33.3%, car by 15.9%, public transport by 8.1% and motorbike/ scooter by 4.6%. The share of the bicycle for commuter traffic in the modal split thus decreased in favour of increased E-bike commuting.

The conclusion by Engelmore (2012) was that regarding energy use and emissions, there are advantages with E-bikes compared with car and bus use. However, their use may lead to a rebound effect related to conventional bicycling when the latter are replaced by the more energy-consuming E-bike.

3.2.5 Well-to-wheel and lifecycle perspective

Another important aspect to consider is the fuel production from an energy perspective, well-to-wheel. A lifecycle approach to energy consumption for production, operation and disposal of the vehicle is also vital when aiming at a fuel shift.

Replacing a fuel may require re-design and switching to alternative powertrain vehicles, which in turn could bring rebound effects from increased energy consumption during the vehicle's entire lifecycle. However, Johansson et al. (2012) point out that the construction, operation and maintenance of vehicles account for only a small proportion of the energy used by the vehicle during its lifecycle.

According to Steen et al. (2013), the energy consumption during vehicle operation depends on several factors. These include are the size of the vehicle, materials selection, energy efficiency, performance, equipment levels, durability and mileage. Energy consumption in the production of both fuel and component materials and technology maturity also affect the car's energy consumption during its lifecycle. The car's weight is very important for total emissions during manufacturing. Steen et al. (2013) reviewed several studies of vehicle lifecycle using a cradle-to-grave approach, but found that it is often unclear how they have been carried out, or which system boundaries have been applied.

Åkerman and Åman (2008) described the energy efficiency of various renewable fuels. In order to compare the fuels, their entire lifecycle was considered in the study. Energy use in fuel production is based on fossil fuels, and represents 5-15% of the primary energy consumed in the lifecycle of fossil fuels. For biofuels, energy inputs in production are larger, because the biomass used as raw material in the process is less refined than the crude oil used in petrol or diesel production. For second-generation biofuels, input energy can at best be limited to about 40% of the primary energy input to the process.

An important factor when calculating the energy consumption for electric cars from a lifecycle perspective is the recovery rate of the vehicle. A high recovery rate can reduce the emissions and energy consumption from the electric vehicle production phase, but this can be difficult to accomplish (SOU, 2013:84). According to Steen et al. (2013), over an assumed total mileage of 150,000 kilometres, lifecycle emissions (and thus energy consumption) from vehicle production can be expected to be significantly higher for a fuel cell car and a battery car than a conventional car, while lifecycle emissions from a plug-in hybrid car differ non-significantly from those of a conventional car.

Åkerman (2012) calculated lifecycle emissions in 2020 for three prototype vehicle types (same size as the Volkswagen Golf or Ford Focus): a diesel car which according to the NEDC driving cycle[11] emits 90 g CO_2/kilometre; a petrol plug-in hybrid with a range of about 50 kilometres on electricity; and a battery electric vehicle with a range of about 150 kilometres according to the NEDC driving cycle. Calculations were based on the assumption of two types of electricity – marginal electricity generation with emissions of 160 g CO_2/kWh and with emissions of 600 g CO_2/kWh. At 160 g CO_2/kWh, the calculations showed that the electric cars were better from a CO_2 emissions viewpoint than the diesel car. The difference was smaller than if only CO_2 emissions while driving had been considered. At 600 g CO_2/kWh, all three car models essentially had the same emissions through their lifecycle. With marginal electricity production with emissions of 600 g CO_2/kWh, 'fuel production' and 'production and maintenance' contributed to the battery car's entire lifecycle carbon emissions. Its lifecycle emissions would thus virtually be of the same magnitude as those of a diesel car or plug-in hybrid, even if the actual driving of the battery car does not produce emissions.

This shows the importance of considering the lifecycle energy consumption from production to recovery for different vehicles types in order to take account of the rebound effects in the transport sector.

[11] http://www.unep.org/transport/gfei/autotool/approaches/information/test_cycles.asp#European

4 Road freight transport

Author: Anna Mellin

Few scientific studies have analysed the rebound effects of measures aiming to increase the energy efficiency in the freight transport sector. In this literature review we found few relevant articles, all of them addressing road transport. This is in line with other reviews of the rebound effect (e.g. Winebrake et al., 2012; De Borger and Mulalic, 2012). The chapter starts with an overview of the studies which address changes in the price of fuel or for the transport service due to an efficiency increase, followed by a section addressing other influences that might lead to rebound effects.

Most of the papers covered by this literature review address direct rebound effects, as discussed earlier in the report. One of these is by Matos and Silva (2011), who estimated the rebound effect on road freight transport in Portugal. They looked at the overall ton-kilometres driven in Portugal divided by total fuel consumption, in order to generate an efficiency measure. They calculated the elasticity of demand for energy with respect to energy efficiency, i.e. the change in ton-kilometres when the energy cost of freight transport is changed (€/ton-km). Their results indicate a rebound effect of approximately 24%.

Another study looked at the rebound effect in the trucking industry in Denmark. De Borger and Mulalic (2012) estimated the rebound effect of fuel efficiency improvements taking into account the fuel price impact on the trucking fleet (i.e. age and size), and the total output produced (measured in ton-kilometres). Compared to Matos and Silva (2011) they are also trying to capture other endogenous effects on the vehicle stock and realized fuel efficiency. They found that output increased by 59% between the years 1980 and 2007, while the energy use increased by 105%. This decrease in energy efficiency is partly explained by increased congestion and new logistic systems demanding goods to be just-in-time rather than in e.g. shop storage units to reduce in-process inventory costs. De Borger and Mulalic (2012) developed a model to calculate the elasticity needed to analyse the rebound effect, and test it empirically by using time series of annual data from Denmark (1980-2007)[12]. The elasticity of fuel use with respect to fuel price was estimated to be rather small, 0.13 in the short run and 0.22 in the long run. Long vs short runs are theoretical constracts that depend on the adjustment time needed to rearrange a firm's production tehcnology. In the short run there is at least one fixed input, in the long run all inputs are variable. In this context, the long run rebound effect is higher because firms rearrange their operation to captilize on the gain in efficiency gain e.g. by investing on more energy efficient truck etc.The authors attributed this to the fuel price also affecting the truck fleet in terms of size and age. They calculated the short-term and long-term rebound effects to be 9.8% and 16.8%, respectively. In numbers this means, a 1% improvement in fuel efficiency reduces fuel use by about 0.90% (short run) to 0.83% (long-run). Their results imply that the increased fuel efficiency reduces the fuel consumption less than proportionately in the trucking industry.

Winebrake et al. (2012) conducted a literature review of rebound effects and heavy duty vehicles (HDV). They noted that the existing studies measure different effects and in different metrics, as well as omitting important elements affecting fuel consumption.

[12] Data used is: ton-kilometre of trucks, vehicle-kilometres, working hours, number of trucks, average age and capacity of the trucks, vehicle-kilometer/liter fuel, fuel price, price index for spare parts and vehicles, and finally wages.

These factors make a comparison between studies difficult and some rebound effects can be misguiding. To their knowledge, no study has analysed the demand for energy or energy services with respect to energy efficiency. However, they found calculations for rebound effect estimates based on energy service price elasticity (i.e. the increase in freight service demand, ton-mile, when the fuel price of freight service, $/ton mile, decreases). They concluded that one reason behind this is that the development in fuel efficiency in the HDV sector has not been at all as strong as that for lighter vehicles (only an improvement of 5%, compared with 67% in the US). This is in contrast to the increase in fuel efficiency in Europe, where e.g. Ruzzenenti and Basosi (2008) found that the road freight transport sector improved energy efficiency by approx. 40% in 1998 compared to 1978.

Winebrake et al. (2012) refer to EPA and NHTSA (2011), which calculated elasticity of demand (vehicle miles travelled) with respect to fuel cost per mile and controlled for gross domestic product , value of goods production, volume of exports and imports and factors affecting the price of trucking. Their calculation generated an estimated rebound effect of 12-45% in the long run and 13-22% in the short run. Anson and Turner (2009) referred to some previous studies on the direct effects of fuel price changes and heavy good vehicles, such as Gately (1990), who estimated a rebound effect of 37%. A review by Graham and Glaister (2002) of rebound effects showed that almost half of the estimates found were within the interval 40-80%.

Somogyi and Török (2010) investigated the emission trends for light commercial vehicles[13]. The stricter emission controls aim at reducing air pollution, but not necessarily fuel consumption. They refer to a study by York (2006) that analysed the effects of the US emission control programme Corporate Average Fuel Economy (CAFE). The results indicated that the energy efficiency of light commercial vehicle has improved by approx. 20% (considering fuel consumption per distance travelled and increased average weight of light trucks). However, the total fuel consumption has increased from 24.4% to 46.6%, and distance travelled and the number of vehicles per capita have also increased.

In general and specifically for freight, a few papers have attempted to estimate the economy-wide rebound effect of energy efficiency for transport[14]. Most of these seem to use general equilibrium models to capture the effects from the transport sector to the rest of the economy. For example, Anson and Turner (2009) looked at the rebound effect in refined oil consumption and supply as a result of increased efficiency in the Scottish commercial transport sector.

Anson and Turner (2009) estimated an economy-wide rebound effect of 36.5% in the short run and 38.3% in the long run. The small difference between the short and long run is explained by the so-called disinvestment effect, meaning that the lower price of energy generates a disinvestment in the energy sector, which reduces the productive capacity in the energy sector. This is in contrast with other research, where the gap is often greater.

An interesting approach to the rebound effect is presented by Ruzzenenti and Basosi (2008). They focused on a macroeconomic level and explained the rebound effects of

[13] No definition of light commercial vehicles is stated in the article but in many cases this is trucks less than 3.5 tonnes.

[14] In economic literature the term leakage is also used which could be seen as economy-wide rebound effect,e.g. that industries are outsourced partly due to strong policies.

increased energy efficiency on globalisation, based on the hypothesis that "*higher complexity counterbalances, on a global scale, the effects of higher efficiency on a process scale*" (Ruzzenenti and Basosi, 2008). They combined thermodynamic-evolutionary theory with traditional economics, where the former theory states that a system with more levels of hierarchy and economies of scale (more specialisation) generates more complex systems. Two of the important drivers for globalisation are increased efficiency of the freight transport sector and the reduction of taxes as trade barriers (Ruzzenenti and Basosi, 2008). Those authors concluded that the rebound effect could be seen from the perspective of the relationship between the energy efficiency of a process and the complexity of a system. This approach describes an example of an economy-wide rebound effect, partly caused by increased efficiency in the transport sector.

Route optimisation can lead to time savings for freight. This saved time can be used to carry out more runs, which means a rebound effect. The evaluation of the Stockholm congestion tax trial showed that distribution was cut to shorter transport times, as it was faster to arrive at many entrances, and the delivery rate increased to about five deliveries per hour compared with four prior to the trial. Distribution transport can thus be performed more efficiently, in this case due to less congestion. However, this can cause a rebound effect when shorter transport times lead to increased demand for transport (Svahlgård et al., 2006).

Piecyk and McKinnon (2010) performed a scenario analysis of road freight future carbon footprint based on a Delphi study. In one of their scenarios they suggest that a decline in fuel efficiency could occur due to increased congestion or stricter regulation of other emissions (e.g. Euro classes). According to the European Commission (2007), the Euro 6 regulation introduced in 2013 generates a 2-3% increase in fuel use.

Creutzig et al. (2011) evaluated different climate policies for road transport, both passenger and freight. They looked at policies regulating carbon intensity, e.g. the Fuel Quality Directive in the EU, and energy intensity, e.g. EU limits on average CO_2/km for cars. To handle rebound effects, it is important to have suitable policies, and those authors argue for quantity instruments to regulate absolute emissions in combination with a clear price signal. One example is a cap-and-trade scheme. This, together with a change from regulations of volume and GHG-based standards to energy intensity-based fuel standards, would be needed to coherently regulate alternative fuels.

The EU is promoting a modal shift from road to intermodal transport, i.e. combined transport with either sea or rail, as one of its main measures to obtain more sustainable freight transport (Tsamboulas et al., 2007). Winebrake et al. (2012) discussed the potential that rebound effects of lower freight prices for road transport can generate an opposite modal shift from more energy-efficient modes such as rail and sea.

Hence, the benefit of an efficiency measure could decrease the total energy savings, since goods are transported with a less efficient mode. No quantification of these effects is estimated and they are limited to certain segments that are more prone to a shift. Furthermore, a modal shift to sea transport would demand in many cases increased speed and more efficient cargo handling to attract new commodities. Increased speed generates highly increased fuel consumption, and fast cargo handling systems such as RoRo (roll-on/roll-off) are very inefficient in load capacity compared with other ship types. Moreover, the total environmental burden is not always beneficial for all ships or trains (when run on diesel) when trucks also become more efficient and less polluting, as shown by Hjelle and Fridell (2012).

5 Aviation and waterborne transport

5.1 Aviation

Authors: Joanna Dickinson and Annika Jägerbrand

Few studies have examined rebound effects in the aviation sector and in this literature study we found only one main paper, by Evans et al. (2013). This described a quantitative estimation of the direct rebound effect in terms of energy use, related to a reduction in marginal costs for aviation when new technology that reduces fuel consumption is introduced. The estimation was based on a model simulation of passenger and airline behaviour. The scope of the estimation was an air traffic network including the 22 busiest airports within the domestic US aviation sector.

The authors underlined that because air traffic grows rapidly and because there are also as yet limited possibilities to reduce GHG emissions from it, the rebound effect is an important matter to consider for this sector. The model simulation showed that passenger demand increases on average by 0.07% for every percentage reduction in aircraft energy use. This increased demand is partly explained by decreased airfares, on an average by 0.23% for every percentage reduction in aircraft energy use (Evans et al., 2013). Increased demand for air travel results in an increase in aircraft operations as well, by on average 0.12% for every percentage reduction in aircraft energy use. When operating costs are reduced, it allows for an increase in occurrence in air traffic, so that aircraft operations increase at a somewhat quicker rate than the increase in passenger demand.

For every percentage reduction in aircraft energy use, Evans et al. (2013) found that the average simulated flight arrival delay increased on average by 0.49% at a 30% reduction in aircraft energy use. How much flight arrival delay would be affected depends on how constrained the air traffic system is to begin with.

It was found that the reduced fuel consumption was not large enough to drive significant changes in network routing of the air traffic, nor did average passenger travel times between origin and destination (flight delays not included).

The reduction in aircraft fleet energy use per seat-kilometre, along with the described adjustments of passenger demand growth, aircraft operations and average delays, led to a resulting simulated decline in system-wide energy use corresponding to 0.81% for every percentage reduction in aircraft energy use, which corresponds to an average rebound effect of 19%.

This estimated direct rebound effect for reduced fuel consumption in the aviation sector is well within the 10-30% range of estimated rebound effects for passenger car travel as identified by Greening et al. (2000). A sensitivity test of the simulation carried out by Evans et al. (2013) showed that airline operational effects and congestion effects may have a notable impact on the magnitude of the rebound effect – increasing and decreasing, respectively, the direct rebound effect by 3 percentage points.

Evans et al. (2013) concluded that a direct rebound effect from lower fuel consumption in aviation may have a stronger effect in the emerging markets of the developing world.

5.2 Waterborne transport

Authors: Annika Jägerbrand & Anna Mellin

Rebound effects within waterborne transport have not been thoroughly studied. Waterborne transport is often more energy-efficient than other transport modes (IPCC, 2014). However, direct CO_2 emissions per distance vary widely depending on type and size of the ships (Walsh and Bows, 2012). For example, estimates show approximately 20-150 gCO_2 per passenger-kilometre for passenger transport and ~2 gCO_2 per ton-kilometre for bulk shipping (IPCC, 2014).

A case study by Hjelle and Fridell (2012) showed that short sea shipping (SSS) by RoRo and container services may be CO_2 efficient but that this depends largely on speed, load factors and distance of operation. Furthermore, they concluded that the advantage of RoRo compared with truck transport in terms of CO_2 emissions may be small and depends on the market conditions and loading factor achieved. Ships of smaller size than used in the case study by Hjelle and Fridell (2012) (i.e. 10 000 deadweight tonnage (dwt), RoRo and 13 000 dwt, container vessel) will lead to higher CO_2 emissions per ton-kilometre. When comparing waterborne shipping with other transport modes, it thus seems crucial to compare net cargo transported (Hjelle and Fridell, 2012).

Waterborne freight shipping is assumed to have low marginal costs and price elasticity is regarded as small, within the range of -0.06 to -0.25 (Buhaug et al., 2009). Therefore, for most types of maritime shipping, rebound effects are assumed to be insignificant. However, one exception is SSS, where price elasticity of demand for transport of general cargo is higher in some cases (Buhaug et al., 2009).

Due to a lack of studies in this area, it is difficult to know how large the price elasticity generally is, especially in Sweden, and there are no known examples of rebound effects on shipping per se from the literature. Nonetheless, price elasticity in waterborne passenger transport may be larger than for shipping freight transport, since travel time, costs and mode of transport are dependent upon individual consumers and their behaviour (see e.g. Adler et al., 2010). Therefore, hypothetically, ferry passenger transport or waterborne tourist transport may show rebound effects to energy efficiency measures.

Furthermore, rebound effects may take place when a modal shift occur between shipping and other transportation modes. From 1 January 2015, tougher requirements on the sulphur content of marine fuels in the Baltic and North Sea (SECA) come into force. The new requirements mean that the sulphur content of the fuel must not exceed 0.1% by weight and the purpose is to reduce air pollution. The new Sulphur Directive is based on a decision by the IMO's environmental committee in 2008. Studies show a potential risk of increased energy consumption (indirect rebound effect at the system level) due to certain transfer of freight transport from sea to road (Näringsdepartementet, 2013).

Based on the few studies available, it seems possible that rebound effects exist within certain areas of waterborne transport, such as passenger transport and SSS, but also when considering modal shifts in a system analysis approach.

6 Artificial lighting

Author: Annika Jägerbrand

Figure 4 Europe at night. A composite assembled from data acquired by the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite. NASA Earth Observatory image by Robert Simmon, using Suomi NPP VIIRS data provided courtesy of Chris Elvidge (NOAA National Geophysical Data Center). Data from nine days in April 2012 and 13 days in October 2012.

Artificial lighting is global and substantial (Figure 4) and has repeatedly been the focus of discussions on rebound effects of energy-efficient measures or technical developments for improving lighting techniques. Artificial lighting consumes 19% of total global electricity production, while causing 1900 Mt of CO_2 emissions per year (OECD and IEA, 2006). Despite large historical gains in energy efficiency of artificial lighting during the past three centuries, increased luminous efficacy is leading to an increased demand for energy for lighting, resulting in an overall rebound effect of 100% (Tsao et al., 2010; Saunders and Tsao, 2012). Furthermore, light emissions have increased rapidly worldwide, with associated environmental effects (e.g. Cinzano et al., 2001; Hölker et al., 2010), causing serious concerns for current and future pollution effects.

Artificial outdoor light consumes high amounts of energy due to the long burning hours (in Sweden approx. 4000 hours per year) and in the case of road and street lights high wattage is usually used to create minimum levels of luminance and thus traffic safe road environments. Road lights usually have long operation times, spanning 30-40 years in some cases. Hence, it is common for municipal lighting to be old and not very energy-efficient, since outdated light sources and techniques are still in service. For example, in a study in 2010 that investigated how much mercury vapour lighting had been replaced in 12 Swedish municipalities found that 50% of the municipalities had more than 20% mercury vapour lights remaining (Jägerbrand and Robertson, 2013). There was a significant correlation between annual energy consumption per light (kWh/light/year) and the percentage of mercury vapour lamps in the municipalities.

Much research aimed at more energy-efficient lighting has concentrated around technical developments leading to use of new light sources, but some studies suggest other kinds of measures or strategies to achieve increased energy efficient lighting (e.g. Boyce et al., 2009; Kostic and Djokic, 2009), see Table 5. Usually, the measures involve either cutting the amount of energy used or increasing the light levels by increased luminous efficacy per kWh.

Table 5 Examples of energy-efficient measures for artificial outdoor lighting.

Energy-efficient measure
Reducing time of burning hours
New technique
More efficient light sources
New design
New standards
Change the number of lights

Worldwide, many countries have adopted a ban on the import and sale of incandescent light bulbs (International Energy Agency, 2010). In Europe, the adoption and implementation of the EU directive on ecodesign requires a phase-out of incandescent light bulbs (also called mercury vapour lamps) by 2015 (EC No 245/2009). Incandescent light sources are therefore being replaced by other types of light sources, such as compact fluorescent lights (CLF) or light-emitting diode lamps (LED), often leading to substantial energy savings in the lighting installation.

However, if the replacement by more energy-efficient lighting techniques affects the use of the services, the energy savings might not be as large as calculated on a purely engineering-economic perspective. Switching to a new light source that consumes less energy may lead to increased usage, for example, keeping the lights burning for longer hours than previously. Furthermore, households may increase the number of lights, as well as increasing the luminous efficacy. Such behaviour changes may lead to increased energy use and rebound effects and have been studied in households in e.g. Great Britain and Germany (e.g. Fouquet and Pearson, 2006; Schleich et al., 2014).

Road lighting is an integral part of the transport infrastructure and may account for as much as 50% of the total energy consumption for the construction, use and operation of a road when calculated based on a lifecycle perspective (Stripple, 2001). Public outdoor lighting have received less attention when considering rebound effects, but from a historical perspective it is certain that rebound effects have taken place (see e.g. Fouquet and Pearson, 2006; Tsao et al., 2010; Saunders and Tsao, 2012; Kyba et al., 2014).

The history of artificial lighting shows that every revolution in light services and technical developments has led to large increases in energy consumption. A study by Herring (1999) showed that public lighting in the UK has continuously increased between 1920 to 1996, resulting in a 30-fold increase in energy consumption and a 20-fold increase in efficiency, with a concurrent increase of mileage of roads of only 50%. Similarly, light intensity (in lumens per watt) of public lighting increased over four hundred-fold between 1920 and 1996 (Herring 1999). Another study showed that on generally introducing electricity in the UK (1920-1950), prices fell 20-fold while consumption increased 10-fold (Fouquet and Pearson, 2011).

It is therefore very likely that similar rebound effects will take place in the future as well when switching to SSL (i.e. LED; OLED; PLED). Currently, such light sources are still somewhat expensive in comparison with traditional light sources, but prices are anticipated to decline. Whether or not such a price fall will lead to similar large rebound effects as has been seen historically depends probably also on the human need for increased light. Fouquet and Pearson (2006) concluded that the limitless demand for increased lighting in history does not necessarily mean that the same will happen with SSL, because the need for more light (as seen for example when switching from gas to electric light) is perhaps saturated nowadays, since most places are currently lit well enough. This is also supported by data from 1920-1996 showing that consumption has levelled off since 1990 (Herring 1990) (Figure 5).

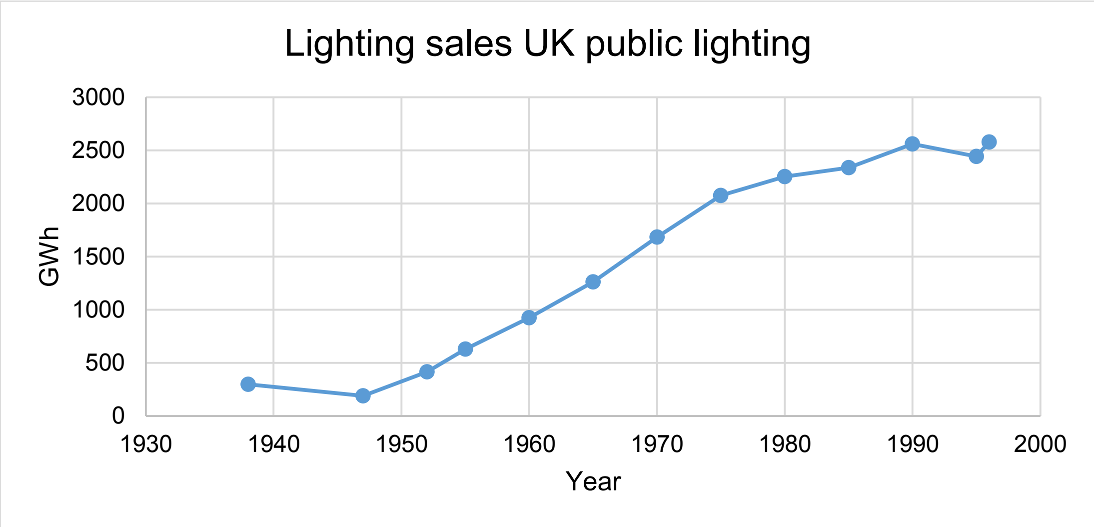

Figure 5 Lighting sales (GWh) of UK public lighting 1938-1996. Data from Herring (1999).

Public lighting on transport roads in Europe is regulated by European standard EN13201 (EN 13201-2 2003), but the standard does not restrict the use of too high levels of lighting but instead requires minimum levels of luminance and luminance uniformity on the road. In fact, energy efficiency evaluation of road or street light installations is voluntary and there is currently no standard on how to perform such evaluations or which factors should be included, although such methods are currently available (Pracki, 2011; Pracki and Jägerbrand, 2013).

Traditionally, light designers anticipate the decline in light loss caused by ageing of the light sources and as luminaires get dirty by compensating with initial over-lighting (e.g. Boyce et al., 2009). New installations therefore produce light levels above the minimum luminance levels required by the European standard. It is not uncommon to see examples of over-lit street and road lighting installations (e.g. Jägerbrand and Carlson, 2011; Kyba et al., 2014). For example, initial over-lighting can be 40% but depends on the light source and luminaire (Boyce et al., 2009). Furthermore, when upgrading street lights, traditional recommendations may restrict the use of more energy-efficient lights with lower wattage effects. For example, substituting 400 W mercury vapour with 150 W high-pressure sodium lamps is considered equivalent, even though a 100 W high-pressure sodium lamp would fulfil the requirements in light levels (see Kostic and Djokic, 2009).

Rebound effects in public lighting are probably much dependent upon price elasticity, as shown in other sectors. In governmental and municipal organisations, economic resources for replacing old luminaires can be limited, while costs for operation and maintenance and energy consumption are normally planned within the yearly budget

(Jägerbrand and Robertson, 2013). Thus, maintenance and operation costs are prioritised by the municipality while new investment or replacement of obsolete lighting is more difficult to obtain because of longer planning and decision-making processes.

It is likely that some municipalities in Sweden suffer from economical limitations and there are examples of towns in Sweden that have shut down road lighting in order to save money on energy spending. Examples include shut-down of operation during summertime, shut-down during night time in winter or a complete shut-down due to economic crisis or to create savings for replacement of mercury vapour lamps. Furthermore, municipalities can sometimes access government funding to replace or improve their road light in order to become more 'sustainable' (i.e. more energy-efficient). Nevertheless, in a study examining decision making on public lighting in 12 Swedish municipalities, none of the municipalities indicated that cost was a barrier for replacing the road and street lighting (Jägerbrand and Robertson, 2013). Instead, renewal of lighting was considered an opportunity to save energy and money. One municipality used the energy savings from replacing mercury vapour lighting to hire an energy expert.

In Sweden, there are discussions on making the outdoor environment equal for all genders and special programmes for such actions have been implemented, leading to changes or increases in the number of luminaries installed, for example in town centres or park areas that are used by pedestrians and cyclists. Perceived safety and increased lighting are also used as a political argument for increasing public lighting and the use of sustainable transport modes (bicycling and walking). When such programmes are implemented, their financing may be sponsored by additional money from the municipal budget. Thus, even though the municipality has financial constraints for new lighting, there are examples showing that it is still possible to increase the number of luminaires.

In public lighting, there are huge risks of the occurrence of shifting baseline syndrome (SBS). Shifting baseline syndrome was first described by Pauly (1995) when discussing how the baseline of fisheries changed for each generation of fisheries scientists. Typically, when starting their carriers, the scientists accepted this as a baseline or starting point, judging changes in species and stocks from this specific point (baseline) in time. For each new generation that started their carriers, the fish stock had declined further, but this was viewed as the normal state by the new generation. Thus, generation by generation, the baseline gradually shifted, fish stocks declined and overfishing occurred. Shifting baseline syndrome can probably also be happening with artificial light, since every new generation becomes used to the existing level of light, thereby shifting the baseline of acceptable outdoor lighting levels (see also Kyba et al., 2014). However, SBS has not been scientifically proven to occur for lighting.

Switching to more energy-efficient lighting technology seems to be able to save energy, but in the long run there are high risks as history shows that such developmental changes may lead to large rebound effects over and over again.

7 Technological developments

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This chapter deals with some of the challenges met when discussing technological developments for reducing GHG emissions and rebound effects.

IPCC (2014) identified transport technologies and practices with potential for GHG reduction. Abstracted from IPCC (2014), pp 45-47:

"Fuel carbon intensity: fuel switching.

- *BEVs (battery electric vehicles) and PHEVs (plug-in hybrid vehicle) based on renewable electricity.*
- *CNG (compressed natural gas), LNG (liquefied natural gas), CBG (compressed biogas) and LBG (liquefied biogas) displacing gasoline in LDVs light duty vehicles) and diesel in HDVs (heavy duty vehicles).*
- *Biofuels displacing gasoline, diesel and aviation fuel."*

Moreover, energy intensity/efficiency of technologies, such as improved vehicle ICE technologies, is also considered important for GHG reductions.

The report by IPCC (2014) focuses on behaviour shifts in combination with a lower carbon system, lowering energy intensity and reducing carbon density of fuels. Improved vehicle performance and engine technologies is also mentioned as one of several mitigation measures with high potential.

Technology policies and developments aimed at reducing carbon emissions or energy use have been discussed in the scientific literature because they result in a reduction in the unit price of energy services, with rebound effects as an indirect consequence (e.g. Greening et al., 2000; Binswanger, 2001; Herring and Roy, 2007). Technological development may lead to increased energy use at a macro-economic level (Herring, 2005).

There is a difference between energy conservation and energy efficiency, defined by Herring and Roy (2007) as: "*energy conservation is generally considered to mean reduced energy consumption through lower quality of energy services*", while energy efficiency is "*simply the ratio of energy services out to energy input*". Thus, energy conservation means reducing consumptions, for example in terms of vehicle speed, or lower temperatures, whereas energy efficiency means getting more for each unit of energy.

In transport, technological developments have resulted in more fuel-efficient cars, but also in consumers choosing less fuel-efficient, larger or stronger cars (Herring and Roy, 2007; Lindgren, 2010). Thus, the potential energy savings for the past 20 years of improved vehicle efficiency have been eaten up by direct rebound effects caused by changed human behaviour.

In Sweden, Sprei et al. (2008) estimated whether technological development in the Swedish car fleet had resulted in energy savings by lower fuel consumption or whether such developments were offset by 'service attributes'. Service attributes were defined as features that appeal to the buyer of cars, such as passenger space, top speed and time for acceleration. Sprei et al. (2008) also included physical attributes specified by the automakers, such as characters that influence fuel consumption, e.g. area, weight, maximum power, cylinder displacement volume, and rolling resistance coefficient.

The development of service/consumer amenities was then compared against fuel consumption between 1975-2002 with statistical analysis and combined modelling of sales statistics and vehicle attributes. Sprei et al. (2008) concluded that 35% of the technological and design development resulted in a net decrease in fuel consumption, while 65% "*served to meet consumer demands*". Thus, the rebound effect for technological developments in the Swedish car fleet was 65% between 1975 and 2002.

Rebound effects arose since consumer demands for e.g. increased passenger space and improved vehicle acceleration increased for the new car fleet. Older and energy ineffective vehicles were replaced by more energy-efficient vehicles, but consumer demand for more space and horsepower resulted in overall increased fuel consumption instead of energy conservation or energy savings effects. The increased demand for larger cars, increased acceleration and higher vehicle weight would have yielded 23% higher fuel consumption (higher passenger space 10%, improved acceleration 8%, net weight 5%) without the technological development.

Other important technological developments causing rebound effects are for example substitution effects induced by fuel efficiency, replacing capital and labour with energy, as well as indirect effects such as spending money on a flight when saving spending on e.g. heating system (Herring and Roy, 2007).

Economy-wide effects are also important when considering technological development and have been shown to occur, especially for electronics and lamps. In the long-run, lower energy costs also greatly affect technological innovations and energy consumption, resulting in new products and services, leading to increased energy consumption. This is especially visible for lighting (Chapter 6). Furthermore, due to the connection between economic growth and technological revolutions, rebound effects may be much greater than 100% (see discussion in Herring and Roy, 2007). Consequently, even though it sounds inconsequent, the best way to save energy is perhaps by not stimulating energy efficiency.

Another important aspect of rebound effects and transport is the time dimension. Both Binswanger (2001) and Herring and Roy (2007) point to the importance of time when discussing technological innovations and rebound effects. They argue that time-saving technological innovations or progress often lead to more energy consumption, especially when wages are high and energy prices low. Yet, there seem to be few studies investigating the combination of time savings, technological developments and rebound effects in the transportation sector.

8 Measures in local transport planning

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Measures aiming to make road traffic flow more efficiently, by achieving shorter travel times by higher speed and/or shorter distances from start to target, may generate rebound effects caused by increased travelled vehicle mileage. The UKERC report (2007) pointed out that there may be a rebound effect with respect to time, meaning that faster cars encourage longer driving distances. Binswanger (2001) examined how time-saving innovations impact on energy use and found evidence that time-saving innovations in transport lead to an increased transport demand, and thus increased energy consumption from transport. The same goes for measures and instruments designed and implemented in urban planning with the aim of reducing climate impact and other emissions from transport by reducing transport demand, or by stimulating modal shift from car use to alternative transport modes such as walking, cycling and public transport. Rebound effects from this type of change in travel patterns are difficult to estimate, but may be extensive. In this section potential rebound effects from reduced transport demand and modal shift in urban areas are examined.

8.1 Increased road capacity

Traditionally, traffic planners forecast increases in road traffic based on factors such as increased population, car ownership and income. Based on these forecasts, new or expanded road capacity is built with the aim of either relieving or avoiding road congestion or letting road capacity respond to the estimated demand (Sanne, 2006). Road investments are often proposed as a measure to accomplish all of these aims.

In the case of increased road capacity aiming to reduce congestion, increased energy efficiency can potentially be achieved if the increased road capacity does make the car traffic flow smoother, reducing queuing. Fuel consumption increases significantly at lower speeds in urban traffic. Reduced congestion and better flow in road traffic thus could make road traffic in a specific travel situation more energy-efficient than a situation with congestion. The same goes for new road investments built with the aim of providing shorter travel times between A and B, with all other circumstances unchanged compared with the pre-investment situation.

However, time savings from higher speed and faster travel over shorter distances and/or reduced travel times from shorter distances or reduced congestion generally lead to increased travelled vehicle mileage and car transport demand (Sanne, 2006; Litman, 2013). The reason is that higher speeds and shorter distances give users increased opportunities to reach more target points within a shorter time, and that road users utilise the time savings they make to travel more and longer. Rather than the new roads in themselves, it is the increased speed and the relative attractiveness that they bring with them that causes an increased demand for travelling by car. . Sanne (2006) pointed out that people often tend to use increased road capacity to travel by car more often and to travel longer distances than they would otherwise have done. For example, when it is faster to take the car to new target locations such as malls, workplaces and neighbourhoods, there will be an increased demand for these trips. . Litman (2013) referred to urban traffic as comparable to a gas that expands to fill the space available. This increased accessibility by car causes an increased demand for car traffic and thus car traffic increases beyond the levels that already existed before the road was built. Sanne (2006) pointed out that urban sprawl is a common consequence of shorter travel times, and that this also generates increased transport demand. There is an relationship between road capacity and transport demand. This phenomenon is termed 'induced traffic' (e.g. Litman, 2013). It is described as increased total vehicle-miles travelled (Litman, 2013) and is caused by shifts from other modes, longer trips and new vehicle trips (European Commission DG ENV, 2011). European Commission DG ENV (2011) also refers to 'generated traffic', defining this as additional vehicle traffic on a particular road which this partly consists of diverted traffic (trips shifted in time, route and destination; European Commission DG ENV, 2011).

Goodwin (1998) underscored that the amount of induced traffic will vary according to the specific circumstances in each case – how much the road capacity increases, as well as the starting point with regard to which alternatives are available both within car transport and other modes, existing traffic congestion, and geographical and economic conditions. Induced traffic includes immediate behavioural adaptations and longer term effects from altered location and land use that with time provide behavioural changes in transport demand. Su (2012) showed that road network density plays an important role in determining travel demand, together with population density.

Goodwin (1998) found that the overall average elasticity of traffic with respect to travel time is about -0.5 in the short run, while an elasticity of the order of -1.0 in the long run seems to be consistent. An elasticity of -0.5 means half the travel time gained is used for new or extended travel. In the longer term, an elasticity of 1 means the entire journey is utilised to make new trips.

Each expansion of the road infrastructure may alter the competition conditions within the transport system. The relationship between public transport and private car travel is affected by increases in the road capacity for motor traffic and this may contribute to rebound effects. Car and public transport are alternative modes that many find possible to choose among. Changes in one system's attractiveness also affects the attractiveness of the other system. An expansion of road infrastructure generally impairs the competitiveness of public transport, a phenomenon is known as the *Down-Thomson paradox*. Jonsson (2002) summarised scientific findings about this phenomenon. New roads initially lead to reduced congestion, and thus to reduced sacrifices in time and cost for the motorists as a result. When the car's attractiveness increases, people who previously travelled by public transport tend to shift to transportation by car. When car travel increases, this leads to reduced demand and revenue for public transport, which in turn leads to higher prices, reductions in offered service and reduced service frequency. As a result, public transport becomes more expensive and less attractive, and this leads to increased modal share for car traffic. The threshold for motorists to switch to public transport becomes higher when the attractiveness of public transport decreases, and the motorists tend to accept worse traffic jams than before as they are now less motivated to switch back to public transport. Road traffic and congestion increase from increased road capacity as a result of the Down-Thomson's paradox (Jonsson, 2002).

Taking these effects in terms of induced traffic into consideration, road planning measures aiming to relieve congestion or shorten travel times by adding expanded or new road capacity have clear rebound effects. However, if induced traffic is not taken into consideration in road planning, the result will be an overestimate of the environmental benefits and congestion benefits of new road capacity. Sanne (2006) pointed out that this implies that the socio-economic benefits of increased road capacity could be generally overstated if the rebound effect of generated traffic is not considered.

8.2 Speed limits

For passenger cars, there is a relationship between increased rolling resistance and increased energy demand when speed is increased. Air resistance and rolling resistance are equal at about 70 km/h for a passenger car. At higher speeds the air resistance dominates. Road speed limits and the road design affect driving patterns and thus the energy consumption of the vehicles (Johansson et al., 2012).

Fuel consumption is a combination of the force needed to overcome the rolling resistance and the driveline capacity. A conventional internal combustion engine in a passenger car has the best efficiency at relatively high load, while the efficiency at low load is usually low. Fuel consumption reaches a minimum at about 70-90 km/h when driving at a constant speed, and increases more steeply as speed increases (SOU, 2013:84).

In a study on possible adaptation to rapidly decreasing availability of fuels in the Swedish transport sector (Neergaard et al., 2010), an analysis of how changed speed limits in the Swedish road network could contribute to reduced fuel consumption showed that if the speed limit on all roads with an existing speed limit of 100 km/h were to be reduced to 90 km/h, and that on all roads with an existing speed limit of 80 or 90 km/h were to be reduced to 70 km/h (except highways in rural areas, which could maintain a speed limit of 90 km/h), total road transport fuel consumption in Sweden would decrease by 3%.

Lower speeds can be achieved through increased compliance with speed limits and by lowering signposted speed limits, and is considered an efficient way to achieve reduced fuel consumption for all transport modes. SOU (2013:84) refers to calculations by the Swedish National Road Administration to cut the current speed limits by 10 km/h (except in rural areas), which could cause a 3-4% reduction in road traffic emissions of CO_2 (Vägverket, 2004). Lack of compliance in the form of speeding offences has been calculated to increase road traffic emissions of CO_2 by about 2.5%, according to data from the Swedish Transport Administration cited in SOU (2013:84). Heavy road vehicles account for almost half of these emissions caused by speeding offences, which is a considerably higher proportion than their share of road traffic.

Indirect effects on fuel consumption from changed speed limits are caused by the change in travel time as a result of the change in velocity. Goodwin (1998) showed that as well as reduced travel times, and of course associated with these, changed speed limits can affect a number of aspects, including route choice, timing and frequency of travel, choice of travel mode and location of housing and businesses, all of which can give rise to indirect effects through increased consumption of journeys. These different effects occur within varying time frames. For example, localisation effects generally occur after a relatively long time.

8.3 Construction and maintenance of transport infrastructure

Energy is not only used to build, operate and dispose of vehicles, but is also consumed in the construction, operation and maintenance of infrastructure, e.g. roads, railways, ports, waterways and airports, according to a summary of scientific studies made by the National Transport Administration (Johansson et al., 2012). Thus, there is potential for energy efficiency improvements associated with construction and maintenance of infrastructure.

Building new roads with the aim of making traffic more energy-efficient by cutting congestion and/or reducing travel times can thus lead to rebound effects not only by induced traffic volumes, but also by the energy consumption from the construction of the new infrastructure and during its maintenance and eventual disposal, when such occurs. In the same way, the energy consumption in a lifecycle perspective must be considered for investments in new railways and harbours etc. with the purpose of stimulating more energy-efficient transport by a modal shift from road transport or aviation, as implied by the summary of studies by Johansson et al. (2012).

From a lifecycle perspective, the construction and maintenance of infrastructure primarily has significance for the energy consumption of roads and railways, but according to Johansson et al. (2012) is less significant in other transport modes. More knowledge is needed about how great the consumption and potential for energy efficiency in infrastructure posture is, but for road transport 10-20% of the energy consumption in a lifecycle perspective is estimated to be related to the infrastructure, and for rail transport 20-50%. Energy use varies widely between specific infrastructure projects depending on traffic, and how advanced the infrastructure is, e.g. elements with bridges and tunnels.

There are many parts of the infrastructure system that can be made more energy-efficient as regards energy consumption in their construction and maintenance and in the traffic using the infrastructure during its lifetime (Johansson et al., 2012). Energy consumption in the construction phase includes mass management, production of materials, paving, etc. The slope of roads and railways affects the energy use from transport. The equipment is connected to the infrastructure, such as ventilation fans, lighting and machinery, is also significant.

Johansson et al. (2012) pointed out that the largest part of energy use and climate impact during the construction of infrastructure is associated with the choice of materials. Calculations of energy consumption for road construction should include the production of the materials needed (Finnveden and Åkerman 2014). Concrete and steel are materials with significant energy consumption. Miliutenko et al. (2012) indicated that energy consumption for production of concrete and steel aimed for road tunnel construction can be at least as large as the energy needed for the construction itself. Paving can contribute to energy efficiency with respect to choice of coating methods, increased durability of the coating and reduced transport of coating masses (SOU, 2013:84). The choice of materials also gives opportunities to improve energy efficiency. A concrete coating has better durability and lower rolling resistance and reduces fuel consumption for transport than a bitumen coating. Meanwhile, cement production is more climate-changing and energy-intensive than asphalt production (SOU, 2013:84).

During the operating phase, there are a number of installations in road and rail systems that use electricity for lighting, traffic signals, heating of railway switches and ventilation fans. Maintenance and operation of roads and railways also requires fuel used for mainly snow removal, deicing, resurfacing and other types of maintenance. The rolling resistance of cars is affected by the choice of material for road coating and how the snow and ice are treated. Reduced rolling resistance for cars leads to reduced fuel consumption, which can lead to a rebound effect from increased driving mileage (SOU, 2013:84). The rolling resistance of trains is affected by the maintenance of the rail (Johansson et al., 2012).

8.4 Intelligent transport systems (ITS)

Planath et al. (2003) conducted a review for the National Transport Administration on the effects of intelligent transport systems (ITS). This showed that ITS are relevant for energy-efficient operations of vehicles since implementation of ITS usually leads to reduced energy consumption. Under the conditions that ITS is implemented for energy savings or to facilitate energy efficient transports, ITS may theoretically cause rebound effects by generating more traffic by increasing accessibility and reducing travel times.

Traffic signals have effects on mobility in the form of shorter journey times for both cars and/or other road users. The same is said to be true for lane control, so-called Motorway Control Systems, where experience from Holland indicates 4-5% higher capacity and a 10-15% reduction in travel times for car traffic in peak hours (Planath et al., 2003). ITS in the form of traffic information via mobile systems, static and dynamic navigation and traffic control, and information with variable message signs to divert traffic at queues and disruption measures will also reduce journey times for road traffic. Tunnel monitoring and control provide short blocking times following accidents and incidents, thus also contributing to reduced travel times.

Dynamic park and ride information is another ITS application that can be judged to have a major impact on travel times to downtown areas. The motorist is kept informed of the current traffic situation and levels and current travel times by different modes of transport. This gives the opportunity to choose the best option in good time before being affected by congestion or other traffic problems delaying the trip (Planath et al., 2003).

8.5 Measures aimed to reduce transport demand and stimulate modal shift

8.5.1 Telecommuting

In recent decades, there has been a discussion on the potential for reduced environmental impact and energy consumption by telecommuting, i.e. whether telecommuting leads to reduced demand for commuting and hence for transport (Arnfalk, 1999). Many studies suggest that there may be a discrepancy between such potential and actual outcomes in terms of reduced transport, caused by rebound effects which instead lead to increased transport.

A survey based on statistics from the national Swedish Travel Survey[15] showed that teleworkers had (almost significantly) higher total travel time than those who do not telework (Haraldsson, 2004). Telecommuters travelled longer distances than those who did not telework, though this difference was not statistically significant. A greater proportion of those teleworking made four or more main journeys[16]. A larger proportion of teleworkers performed 2-5 extra trips per day, while those who did not telework more often only made one extra trip. There were observable differences in mode choice for partial journeys; remote workers travelled to a larger extent by car and by train but were

[15] RES, 1999–2001

[16] Haraldsson (2004) defines a "main journey" as travel between two main starting and end points. The respondent's registered residence, another permanent residence, holiday residence, workplace, school or occasional overnight stay can be counted as main starting or end point. Partial journeys begin and end in a place where the respondent is doing an errand. Thus a main journey may consist of one or more partial journeys and can be seen as a chain of travel that links different errands.

less likely to walk, cycle or use local public transport. However, these differences were not statistically significant either.

Arnfalk (1999) provides an overview of the potential environmental and economic savings from telework (telecommuting) and teleconferencing. He points out that telecommunications could either substitute or supplement existing travel patterns, or even generate more travel. Furthermore, Arnfalk (2013) described the possible rebound effects of increased telecommuting in terms of overall increased transport when congestion in rush hour is reduced as a result of people teleworking, or because of commuting over longer distances when telecommuting enables settlement at greater distances from work (by regional expansion).

Other potential rebound effects of teleworking can accompany a modal shift from public transport to the car, because it becomes less profitable for those who commute to hold a monthly travel pass as the number of commuting days decreases due to teleworking. Another reason is if employers increase the geographical catchment area for the recruitment of labour, by accepting a longer commuting distance for employees who have the possibility to telecommute partly. Telecommuting allows increased travel distances through regional expansion and sprawl when people choose to live further away from the workplace. Arnfalk (2013) refers to studies estimating the rebound effects of telecommuting to be 5.7% of commuting, due to more non-work related trips. 0-50% of the commute could be replaced by other trips because of a latent demand for travel and relocation.

A proportion of the savings in energy consumption when a commuting trip is replaced by teleworking can thus be ‘eaten up’ by other journeys made instead. However, according to Arnfalk (2013), empirical studies in recent years show that the effect where other trips replace commuting journey is marginal, close to zero. The rebound effect of regional expansion (when a person who teleworks lives at a longer commuting distance from the workplace) is estimated to be marginal, according to the studies referred to by Arnfalk (2013). He pointed out that most of these studies were conducted over a limited period, and thus may miss rebound effects that only manifest themselves after a longer period of time. Arnfalk (2013) estimated that one-third of the expected travel reduction is ‘eaten up’ by other travelling. (This means that the net effect of telecommuting is still positive in terms of reduced travel, by reducing travelling by two-thirds.)

A possible rebound effect of telecommuting is to reduce the need for commuting, instead allowing for an increase in other types of travel, such as leisure travel. SOU (2013:84) indicates that the recreational habits of Swedes are largely dependent on the car. One example is that in Sweden there are over 700,000 homes and hundreds of thousands of pleasure craft to which foods and gadgets need to be transported. Swedes’ interest in outdoors contributes to their need for a car.

8.5.2 Mobility management

In the literature describing the effects and potential of different mobility management measures, rebound effects are seldom calculated or described. In this section, potential rebound effects that seem to be important to consider when choosing, designing and implementing mobility management measures are identified.

The underlying objectives for working with mobility management measures and schemes can vary. Common underlying objectives are to reduce climate impacts from CO_2 emissions, to improve the air quality and other environmental qualities in cities, and/or to reduce congestion in road traffic. Closely linked to these objectives is the aim to reduce energy consumption, which is often not explicit but implied. In many cases, reduced energy consumption from transport and increased energy efficiency are consequences of mobility management measures and instruments, without being a purpose (SIKA, 2008; Litman, 2011).

Mobility management can for example include pricing reforms such as increased road and parking pricing, distance-based vehicle insurance and registration fees, and fuel tax increases (Litman, 2011).

Litman (2011) made a comparison of how well mobility management measures and measures aiming for cleaner vehicles comply with a range of different planning objectives[17]. One conclusion was that measures aiming for cleaner vehicles contradict many planning objectives by inducing additional vehicle travel as a rebound effect. Another conclusion was that mobility management schemes to a greater extent contribute to fulfilment of the different planning objectives analysed, including congestion reduction, energy conservation and consumer savings and affordability. This, however, indicates that some mobility management pricing reforms, intended to reduce transport demand and stimulate modal shift from car to less energy-consuming transport modes, could potentially have rebound effects.

Examples of promotion and improvements of public transport causing potential rebound effects have been suggested. For example, zero-fare schemes in public transport have been tried internationally and in some Swedish municipalities. Their principal effect, according to Balcombe et al. (2004), is to attract people who would otherwise walk or cycle. Balcombe et al. (2004) argue that there is no convincing evidence that free travel attracts car motorists to switch travel mode to public transport.

The PROPOLIS[18] project used modelling to study the behaviour of people and businesses with regard to their location choice and travel behaviour in the seven European case cities of Helsinki, Dortmund, Inverness, Naples, Vicenza, Bilbao and Brussels. The results showed that some measures intended to decrease travel demand could in the long-term instead lead to increases in private car mileage. This was especially the case for some public transport policies. Part of the reason for this is that the policies resulted in less congestion in the transport network and thus made it possible for households to move to more peripheral areas while still maintaining their travel budget. This resulted in increases in the average trip length and possibly in car ownership, and thus also in private car mileage (Lautso et al., 2004).

8.5.3 Park and ride

Parking policies can include a variety of instruments and measures. Park and ride means that motorists can park their cars and continue their journey by public transport. Park and ride facilities are generally implemented at public transport hubs, where motorists can park and travel on to the target point by public transport. The objectives are generally to expand the catchment area of public transport, to attract car commuters to switch to

[17] The planning objectives analysed were: improved travel speed, convenience and comfort; congestion reduction; roadway cost savings, parking cost savings, consumer savings and affordablity, traffic safety, improved mobility options, energy conservation, pollution reduction, land use objectives, public fitness and health (Litman, 2012).

[18] PROPOLIS - Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability - a research project within the 5th framework programme of the EC.

more sustainable modes of transport and thereby reduce traffic, and to increase public transport travel into the city centre or the region (Hamer, 2009; Svensson and Hedström, 2010). The amount of car traffic is thereby reduced. This can have a positive effect on the traffic situation by for example reducing congestion in peak hours (Planath et al., 2003). However, this leads to shorter travel times for motorists and can lead to a increased energy consumption by induced traffic. Svensson and Hedström (2010) and Hamer (2009) argued on the basis of available international research that it is uncertain how much park and ride services really help to reduce car traffic or transport in cities, but that there are rather indications that park and ride can cause an increase in car journeys.

Parking policies, such as park and ride, can improve traffic flow and thus lead to increased demand for car traffic. Changed parking rules and physical markings of parking spaces can lead to increased capacity for parking. This in turn makes it easier for the motorists to find car parking space, and makes it more attractive to take the car to the actual area. Again this can cause a rebound effect in terms of increased car traffic (COST Action 342, 2006).

8.5.4 Separated bike and bus lanes

The focus in studies of effect relationships between different types of separated bike and pedestrian lanes is generally on bike and pedestrian traffic, and not on vehicle traffic (Jonsson et al., 2011). In Sweden, separate bike and pedestrian lanes are often allocated besides existing road infrastructure for traffic safety reasons, as part of schemes to increase modal share by cycling and walking. There seems to be a lack of established effect relationships regarding how this type of measure affects vehicle mileage, and thus potential rebound effects from increased vehicle mileage. In general, studies of the effects of the construction of pedestrian and cycle paths completely detached from the street network seem scarce in the literature.

Allocating space to walking, biking and public transport separately from car lanes also makes car traffic flow smoother. This actually makes increased average vehicle traffic speeds possible. In Manhattan, New York, GPS data from yellow cabs below 60th Street showed that average speeds have risen by 6.7% since 2008, when street space was allocated to separate lanes for bikes, buses and pedestrians so that vehicles no longer need to share space with these other transport modes. Engelmore (2012) concluded from model-based analysis of different scenarios of modal split in the city of Groningen that 10% more cycling trips result in a 15% reduction in lost hours for car trips and the average speed increases by 8%. Nilsson (2003) evaluated the effects of construction of bicycle lanes, meaning an area of the roadway separated by road markings and marked with bike symbols, with regard to cyclist safety and the ability of bicycles to compete with car traffic. It was found that these sometimes attracted cyclists from other routes, but in general they did not increase the number of cyclists or reduce the speed of car traffic. Bicycle lanes were not an improvement on minor streets with no midline, as car speeds on these streets increased. Velocity measurements showed that the bicycle lane did not have any general traffic-calming effect. However, they generated increased car traffic speeds on the average 2.9 km/h on collector streets with no midline in residential areas with small traffic amounts. With a street midline, bike lanes meant a diffuse narrowing of the lane and motorists did not need to reduce their speed in order to keep to their lane. Among other streets, bike lanes led to a reduced speed for car traffic, but not significantly. Bicycle lanes were successful when implemented over long distances on main streets linking important destinations for cyclists.

The adverse effect can be seen when redistributing car lane capacity to other transport modes. Lindenmann (2007) reported that while road planning and design for many decades revolved around car traffic capacity and road safety, the trend today is in favour of mixed traffic and shared traffic space instead of separation. He examined how this has led to usable public spaces in the centre of provincial towns and villages in Switzerland, and consequently also to lower speeds in car traffic. An evaluation of the introduction of bike lanes on existing street space with markings on the main street of Hornsgatan in the City of Stockholm in 1999 showed that almost all motorists experienced that their accessibility had become less good (Tjärnberg, 2000).

9 Indirect rebound effects

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According to Broberg (2011), direct rebound effects are estimated by too narrow an analytical framework, as it only applies to individual use of energy, such as passenger car transport. Lower driving costs as a result of more fuel-efficient passenger car transport not only implies a risk of increased car traffic, but can also lead to increased consumption of other goods and services that are energy-demanding.

In comparison to direct rebound effects, these types of indirect rebound effects are less well understood (Nadel, 2012) and there is uncertainty about their size. Indirect effects have been estimated by studying how efficiency improvements affect consumption spending and its allocation among sectors (Michaels, 2012).

A variety of CGE models[19] have been used to estimate such indirect rebound effects. The relatively small number of CGE studies that have estimated indirect rebound effects shows that effects on the entire economy may be even stronger than those of direct rebound effects according to an overview by Michaels (2012), who refers to estimates based on CGE models of the indirect rebound effects to be in the interval 37-100%.

The number of CGE studies is still small but their results so far suggest that the more complex the economy and the longer the time that can elapse, the greater the rebound effects from improvements in energy efficiency (Michaels, 2012).

Nadel (2012) found that both indirect and direct rebound effects exist and that direct rebound effects are generally 10% or less, while the best available estimate of indirect rebound effects is around 11% in total, and 6% for road transport. Nadal argues that these can be added to a total estimated rebound of about 20%, and points out that this still leads to 80% energy savings from energy efficiency programmes and policies, thus regarding the 20% rebound effects as a contribution to benefits for households and society. Nadel (2012) expressed doubts about the existence of a 'backfire' rebound effect of 100% or more.

The economy-wide rebound effect is not very well-documented in the literature, since it is considered very difficult to measure due to methodological problems (IEA, 2012; IRGC, 2013). According to Michaels (2012), no available study has attempted to estimate aggregated economy-wide rebound effects.

Based on the existing literature, Broberg (2011) concluded that the long-term economy-wide rebound effect of energy efficiency in most cases is significantly less than 100% and thus contributes to reduced energy consumption. However, that author claimed that based on the existing research, it is not possible to draw any general conclusions with good precision about the size of the economy-wide rebound effect of individual measures.

[19] CGE, "computable general equilibrium", models are tool kits allowing researchers to compare the estimated effects of policies in detail. The model numerically solves a large system of equations that incorporate the determinants of economic choices made by consumers and producers of the economy's goods and services, based on empirical data and assumptions about economic magnitudes and behavior. CGE are based on utilitarian maximization and perfect market assumptions, rather than empirical evidence (Michaels, 2012).

10 Discussion

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Rebound effects and their size depend on input and output data, time scales, geographical scales, economic situations and study boundaries. There is currently no common agreed methodology on how to measure rebound effects, except for the ratio of potential versus actual energy savings (see for example discussion by Turner, 2012). Thus, not surprisingly, rebound effects have been the focus of both scientific and political debates and the source of disagreements for some time now.

This report comprehensively examined the existence of rebound effects in a number of areas within the transport sector. Several areas where rebound effects occur were identified, but also areas where there are no or little data even in a worldwide perspective. These include aviation, waterborne transport, transport planning, indirect rebound effects, time dimensions of rebound effects and transport and also aspects of human behaviour and transport, to mention a few. Existing studies encompassing a wide range of rebound effects in the transport sector were summarised and areas for future studies from a Swedish context were identified. Furthermore, the report examined the kind of data that would be possible to use in future studies and incorporated the opinions and views from two transport planners.

This Chapter first discusses findings from the most relevant sections in this report and then goes on to discuss the findings from a Swedish perspective. Finally, gaps in current knowledge are identified.

10.1 Discussion on relevant sections

10.1.1 Passenger transport

Direct rebound effects for passenger cars and variables associated with passenger cars have been the subject of many studies in many different ways, making general comparisons difficult. Studies on passenger cars and rebound effects include different time series, countries and include a diverse array of different explanatory variables in different statistical, economic or energy frameworks. Thus, different conclusions can be drawn depending on the studies included in the review.

Broberg (2011) previously reviewed rebound effects and suggested that the rebound effects in the transport sector are within the range 10-70% and that rebound effects in Sweden are probably in the lower half of this range (i.e. 10-30%). The studies reviewed here agree with Broberg's conclusions and suggest that direct rebound effects are in the range 10-70% in Europe and 10-30% in USA. However, rebound effect estimates based on German travel survey data are substantially larger than the typical effects obtained from US studies based on empirical data (Frondel and Vance, 2009; Frondel et al., 2012).

A few studies (e.g. Lin and Liu., 2013) have concluded that there can even be a backfire effect of increased fuel efficiency in vehicles. For China, studies show that almost all, or even more, of the expected reduction in transport energy consumption from efficiency improvement is at risk of being 'eaten up' by direct rebound effects. Likewise, Chakravarty et al. (2013) found that in developing economies, the rebound effect varies from no rebound at all to a backfire effect. These results suggest that developing countries with a large unmet demand for energy will generate a high rebound effect.

However, since rebound effects are also dependent on income and there is a strong linear relationship between income level and travelled distance, the rebound effect in transportation may change over time and in relation to economic and technological development.

Studies indicates that the direct rebound effect for increased fuel efficiency in cars is declining with time (Small and Van Dender, 2007; Sorrell, 2009). Broberg (2011) pointed out that, judging from the literature estimating price elasticity, the long-term rebound effect in most cases is higher than the short-term rebound effect, and is often more than twice as high.

Furthermore, Broberg (2011) pointed out that the price elasticity for fuel efficiency is generally found to be higher than the elasticity for vehicle mileage. The reason for this is that, apart from leading to reduced vehicle mileage, higher fuel costs also lead to other effects affecting fuel consumption, including motorists driving in a more fuel-efficient way, and changing routes in order to reduce fuel consumption, as well as increased use of more fuel-efficient cars.

A direct rebound effect of 10-30% has been suggested by Broberg (2011), which seems to be in line with many other research studies. It could be considered realistic for Swedish conditions. However, such low rebound effects are contradicted by results by Sprei et al. (2008) on the effects of technological developments in the Swedish car fleet 1975-2002, showing a rebound effect of 65% (see below).

10.1.2 Fuel shift

Regarding fuel shift and electrical vehicles, we found few empirical studies examining this particular aspect and its rebound effects, although Kågeson (2013) studied dieselisation in Sweden and concluded that reduced fuel consumption results in an increased mileage, but that the magnitude of the rebound effect is unknown. Also, the price elasticity of fuel and behaviour studies on owner activity of electric vehicles suggest that rebound effects probably exist, and may be substantial.

10.1.3 Road freight transport

There are a few studies analysing the rebound effects of measures aiming to increase the energy efficiency in the road freight transport sector and, as for passenger cars, these studies use different methodology and input data. For example, direct rebound effects on road freight transport are estimated to be 13-22% in the short run and 12-45% in the long run, but there are considerable variations between different studies. Economy-wide rebound effects are estimated to be 36.5% in the short run and 38.3% in the long run.

10.1.4 Aviation and waterborne transport

For aviation, we found only one study examining rebound effects. Evans et al. (2013) showed an average rebound effect of 19% for aircraft in USA. There are no studies on rebound effects for waterborne transport. However, it seems possible that rebound effects exist within certain areas of waterborne transport, such as passenger transport and short sea shipping (SSS), but also when considering modal shifts in a system analysis approach.

10.1.5 Artificial lighting

Public lighting is the only sector within the transport area with extremely long time series of data available, in fact all the way back to 1300. Such data show clearly that developments have led to repeatedly occurring revolutions in lighting techniques/services, inevitably resulting in strong rebound effects (or backfires) in time, over and over again (e.g. Herring, 1999; Fouquet and Pearson, 2006). It is unknown whether the need for outdoor lighting has been saturated in recent decades, but trends in light sales (GWh) in UK since 1990 indicate that the demand might be levelling off (Herring, 1999). Only future studies on solid state lighting can show if the new revolution in lighting technology gives rise to as high rebound effects as previously shown.

10.1.6 Technological developments

Technological developments may lead to increased energy use as an indirect consequence of reductions in the unit price of energy services. In Sweden, technological developments 1975-2002 in the new Swedish car fleet resulted in a 35% net decrease in fuel consumption, while a 65% rebound effect was caused by counteracting effects of consumer demands, causing the car fleet to increase in passenger space, improved acceleration ability and higher net weight of vehicles (Sprei et al., 2008). Thus, energy-efficient technological developments have led to a shift in Swedish car ownership preferences towards higher horsepower cars (Lindgren, 2010). Other rebound effects of technological developments are highly likely but rarely studied, for example substitution effects induced by fuel efficiency, economy-wide effects and time-saving technological innovations.

10.1.7 Transport and community planning

Regarding transport and community planning, we were unable to show any empirical evidence of a rebound effect in the scientific literature except for road investments aiming at reducing congestion and travel times. It is likely that rebound effects exist in the areas of mobility management, road capacity management and park and ride policies, when these instruments and measures lead to shorter travel times for car traffic as an indirect result, and thus indirectly cause increased car transport demand.

The interviews carried out with two transport planners (see Appendix B) revealed that they are aware of objectives for increased energy efficiency, and also of increased road capacity leading to rebound effects in terms of increased vehicle mileage. Increased energy efficiency in transport and a reduced climate impact do not constitute any actual *"point on the agenda"* to date in the transport planning process. The energy efficiency of transport is discussed in transport planning processes, but is only to a small extent taken into account in the decisions on measures that should be prioritised as a result of planning. The interviewees stated that in order to avoid rebound effects, transport planning needs to be aiming at reaching objectives to a much higher degree than today, and that objectives for reduced climate impact and increased energy efficiency need to be prioritised in the planning process.

10.1.8 Indirect rebound effects

Few studies exist and it is considered very difficult to measure indirect rebound effects and economy-wide effects. A few studies suggest that the indirect rebound effects are in the range 10-100%, although it is questioned whether the rebound effect can be over 100% (backfire effect). Nadel (2012) and Broberg (2011) suggest that the long-term economy-wide rebound effect of energy efficiency in most cases is significantly less than 100% and thus contributes to reduced energy consumption.

10.1.9 Human behaviour

Environmental awareness may result in indirect rebound effects being avoided, but it might be more difficult to avoid direct rebound effects, even when consumers have pro-environmental attitudes. A number of aspects need to be considered to fully understand consumer responses to changes in energy efficiency or energy prices, and thus the rebound effects. We found few studies in Sweden on human behaviour, rebound effects and transportation questions. In particular, there is a great need for more research to understand how economics and psychological theories interact.

10.2 Rebound effects in a Swedish perspective

Rebound effects have important implications, undermining the aim of reaching the Swedish climate and energy goals in the future. When planning measures within the transport sector to reduce GHG emissions or reduce energy consumption or intensity, the risk of rebound effects is especially strong when considering the interaction between time, energy and economy. This is due to the fact that transport is more closely correlated with energy consumption than other sectors. To save time in transportation, more energy is consumed, but it may also result in the consumption of more energy-intensive services and products (e.g. Binswanger, 2001; Herring and Roy, 2007).

Indications from the scientific literature and Swedish studies suggest that rebound effects of varying magnitude are present (varying from 10 to 65%) and that there is a risk of energy efficiency measures transferring transport energy savings into other transport modes, sectors or energy services, resulting in zero energy savings or, even worse, increased energy consumption.

To correctly estimate the total effects of energy efficiency measure within transport, it is important to understand human behaviour and decision-making processes and to measure net energy consumption in a systems perspective, without limiting data input to e.g. a single transport mode. This will have direct effects when implementing different policy measures, and it is important to analyse policy package when risk for high rebound effects exist.

10.2.1 Current gaps

We identified the following gaps on the study of rebound effects related to the Swedish transport sector.

Firstly, as Appendix A shows, there are a number of data available for calculating rebound effects of passenger cars, freight transport and substitution effects (see e.g. Borger et al., 2013) in Sweden. Such calculations could show whether or not Sweden's environmental measures and policies are effective and how large the direct rebound effects are in quantitative terms. One crucial aspect for more energy-efficient transport is the fill rate for transport, particularly when considering modal shifts. For example, within short-distance waterborne transport (SSS), the load factor may be an important indicator of whether such transport is more energy-efficient than road transportation. Since such aspects will greatly affect the total energy savings, rebound effects will probably be affected.

Economy-wide and indirect rebound effects have never been studied in Sweden, even though GHG emissions from international bunkers (aviation and waterborne transport) are clearly showing an increase, while GHG emissions from domestic transport are slowly decreasing (passenger cars) or not increasing as much as previously (freight transport). Furthermore, economy-wide rebound effects in combination with large technological developments may lead to substantial rebound effects. Since the vehicle fleet is anticipated to undergo several fuel shifts and successive energy efficiency developments, studies on how such changes may affect travelling behaviour and indirect rebound effects should be prioritised. Otherwise, there is a risk of counteracting developments of energy-intensive services or goods. For indirect and economy-wide rebound effects, it is important to consider total energy consumption from a lifecycle or well-to-wheel perspective.

Human behaviour that may directly affect or counteract politically decided measures and goals has not been studied in detail to investigate attitudes and reasons for the emergence of rebound effects on the individual level. For example, the media in Sweden recently reported a sudden decrease in the use of ethanol fuel consumption (E85), in spite of the fact that ethanol is subsidised and thus cheaper than petrol. The phenomenon has been discussed as an expression of lack of trust in the quality of the ethanol fuel, causing consumers to switch to petrol in order to save money on future vehicle repairs caused by ‘bad’ ethanol.

The lack of studies on human behaviour is especially troublesome, since even perceptions of being environmentally friendly and acting in support of sustainable transport does not constitute a hindrance to the emergence of (economy-wide or direct) rebound effects. Thus, studies are urgently needed to better understand human behaviour from the aspects of economics, psychology and energy efficiency, and their interactions.

Anticipated large/dramatic technological developments are clearly particularly important to study from a rebound effect perspective, since historically such developments have always led to increased energy intensity and rebound effects. Since large technological developments leading to enhanced energy efficiency within both transport and artificial lighting are foreseen during the coming decade, it appears to be important to fully investigate how large such rebound effects may become. However, rebound effects are highly dependent on economy, income level and the developmental condition of the country, so it can be argued that historical backfire effects are not certain to recur under future circumstances, but may depend on economic growth. Nevertheless, large rebound effects due to technological developments or breakthrough are still anticipated to occur, so it must be considered a high priority area of research to investigate the size of energy savings in the perspective of rebound effects.

Rebound effects may exist as a side-effect of transport planning. If road planning or infrastructure is planned with the goal of increased energy efficiency, it should be possible to analyse rebound effects before and after. Hence, rebound effects should be included in projects that strive to reduce energy efficiency. However, there are methodological problems in measuring rebound effects in transport planning due to the existence of indirect rebound effects, because these will be difficult to determine but will probably represent a large percentage of the total rebound effects for a project.

Finally, transport planners and policy makers need to be informed about the size of potential rebound effects, but the lack of empirical evidence and other detailed information makes it difficult for them to take rebound effects into consideration when making decisions. Thus, the lack of studies on rebound effects in Sweden creates difficulties in anticipating demands and potentially increased energy use.

10.2.2 Rebound effects and reaching Sweden's climate and energy goals

Rebound effects should be included when calculating whether Sweden will reach its climate and energy goals, especially within the transport sector, where rebound effects are assumed to be particularly large within specific transport modes and over time. Unfortunately, in many cases, the rebound effects are currently unknown, and there are many factors that may affect their magnitude and scale. In cases where rebound effects are considered to be large or substantial or even cause backfire effects, it is often considered important to implement measures or policy instruments to reduce the rebound effects.

We found it very difficult to make any predictions on to what extent rebound effects will influence the possibility to achieve climate and energy goals set by different measures and policies. As shown in this study, several empirical studies have been conducted in other countries, however the possibility to transfer those results for Sweden (i.e. benefit transfer) is not always appropriate due to e.g. context specific conditions. Moreover, it is not fully clear how the energy consumption and GHG emissions of different transportation modes must be affected in order to reach the climate and energy goals. Furthermore, current energy and climate policies have been criticised because they comprise a mixture of subsidies, taxes and other policy measures, making implementation of measures for achieving the goals expensive and ineffective (Konjunkturinstitutet, 2013).

Nevertheless, studies on rebound effects from other countries with similar economic conditions as in Sweden show that rebound effects exists, and these countries have therefore included rebound effects in their analyses order to fully understand measures and nationwide responses more accurately.

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Appendix A. Available data and sources of information in Sweden

Authors: Staffan Dahlberg & Annika Jägerbrand

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Introduction

There is plenty of data available to estimate rebound effects in similar studies as Kågeson (2013) performed on passenger cars, fuel consumption, kilometer travelled and age of vehicle fleet, as well as more detailed studies on correlations between transportation preferences and household factors such as demography, age, economy, and geography and so on.
There are also data available for trucks on fuel consumption, kilometer travelled and age of vehicle fleet, but without proper freight data it is difficult to calculate rebound effects.

Passenger cars

For passenger cars, fuel consumption, consumption of renewable fuels and traffic work, data are available at the Swedish Motor Vehicle Inspection company (Bilprovningen 2014) and transport analysis (Trafikanalys 2014). Here, we present some relevant data and recent developments regarding to passenger cars, consumption of renewable fuels and rebound effects.

The amount of passenger cars by fuel type has changed during the latest 10 years, shifting to an increase in alternative fuels. Diesel cars account for the largest share and have increased substantially during the latest decade.

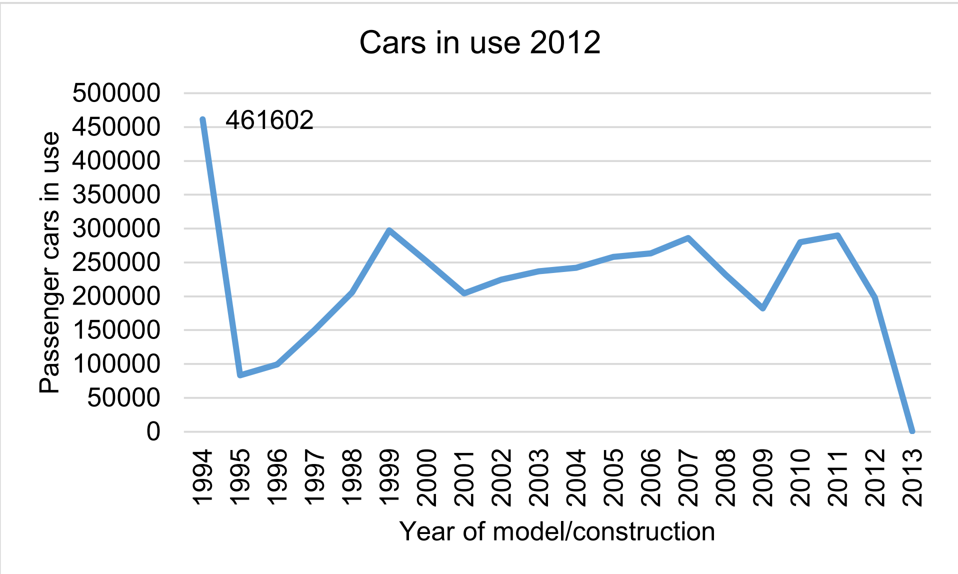

Figure 1 Number of passenger cars in use per year of model/construction in 2012. Data shown for 1994 and includes 1994 and all previous years. Data from Trafikanalys.

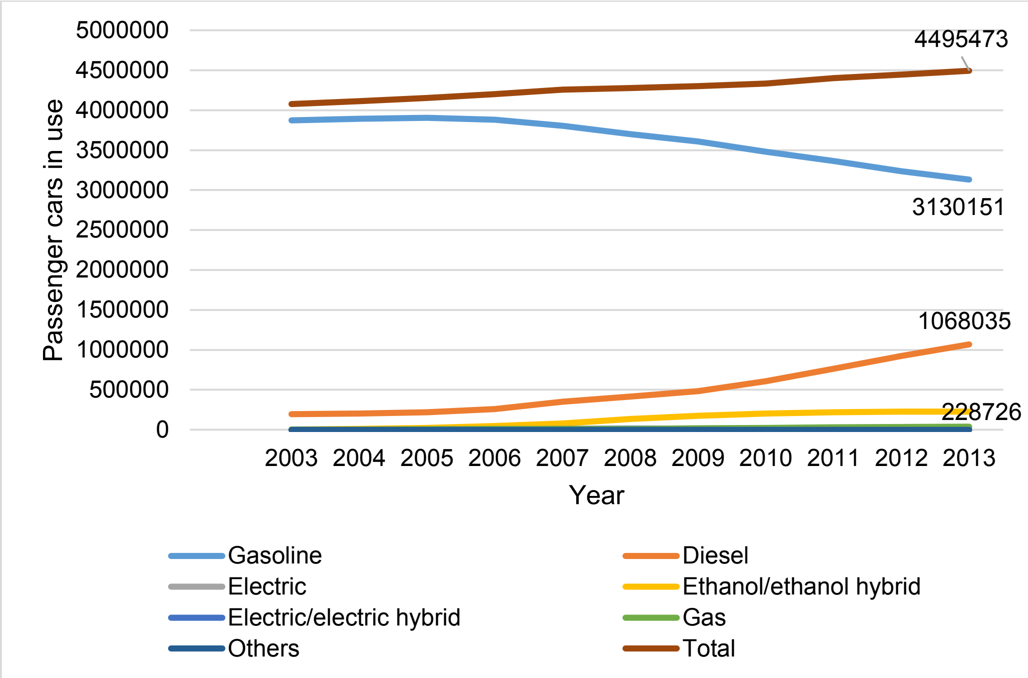

Figure 2 Passenger cars in use by fuel type 2003-2013. Numbers shown for total, gasoline, diesel, and ethanol/ethanol hybrids passenger cars for 2012. Data from Trafikanalys.

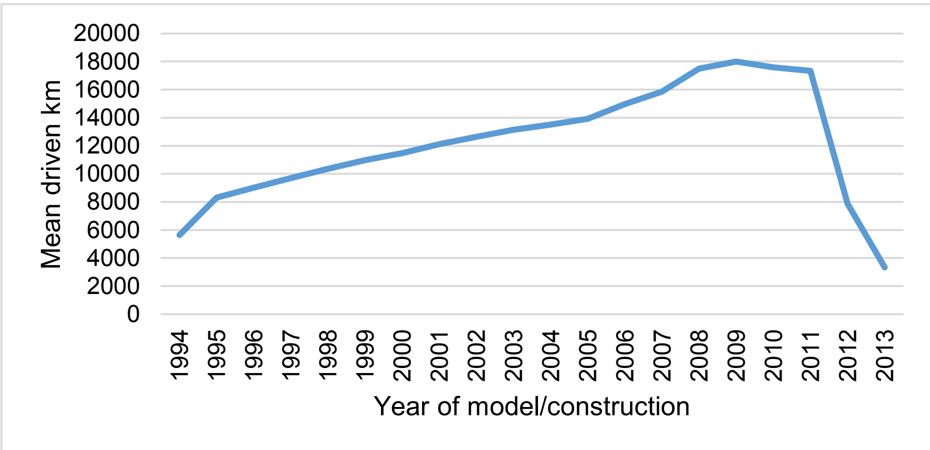

Figure 3 Kilometers driven and number of passenger cars by year of model/construction and owner, year 2012. Data from Trafikanalys.

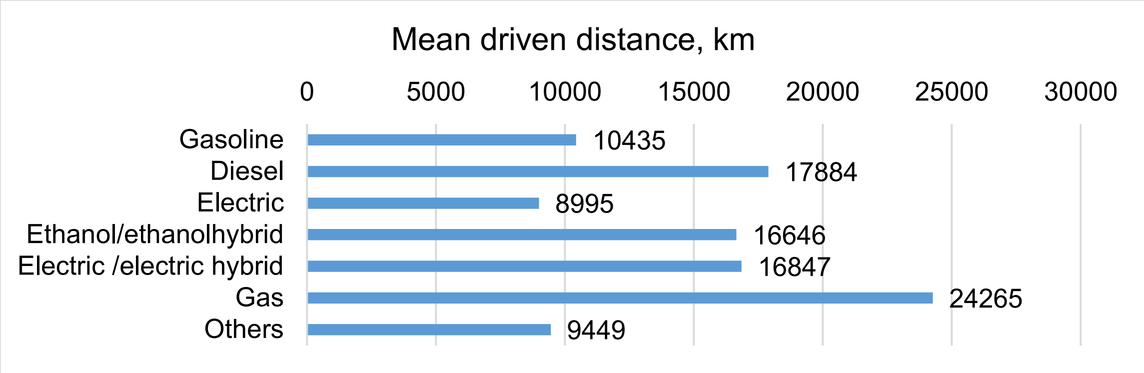

Figure 4 Mean driven distance (km) and number of passenger cars by fuel and owner, 2012. Data from Trafikanalys.

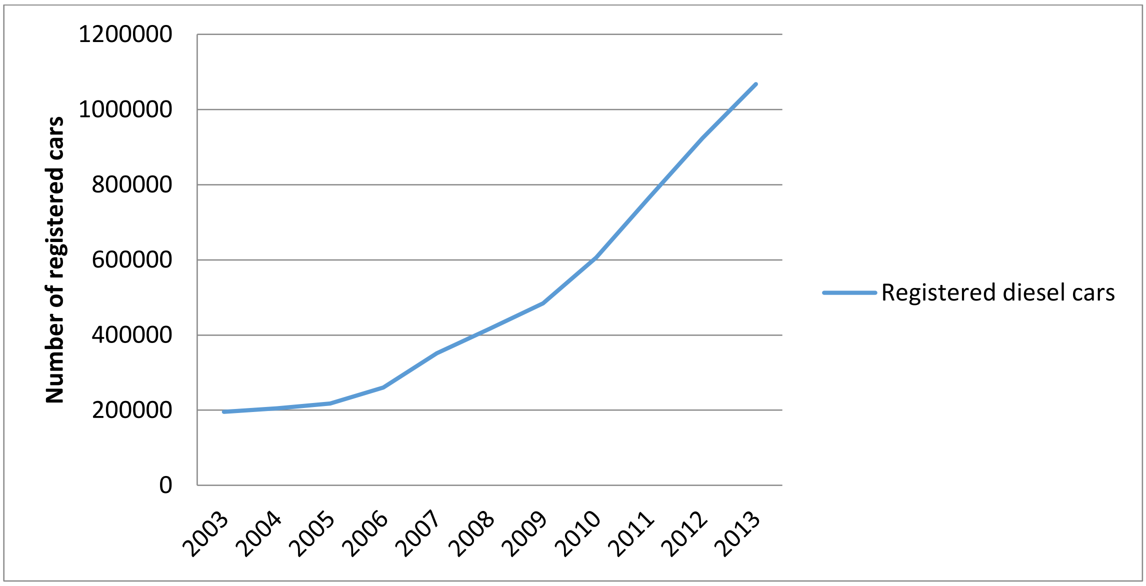

Figure 5 Number of newly registered diesel cars 2003 – 2012. Data from Trafikanalys

Table 1 Car turnover rates. Mean values of new registrations and deregistrations, 2003-2012. Data from Trafikanalys.

	Total number of registered cars	New registrations		Deregistrations	
Year		**Number**	**%**	**Total**	**%**
2003	4075414	307068	7.53	254545	6.25
2004	4113424	311536	7.57	242979	5.91
2005	4153674	311779	7.51	252525	6.08
2006	4202463	313812	7.47	290245	6.91
2007	4258463	338538	7.95	243674	5.72
2008	4278995	276344	6.46	178955	4.18
2009	4300752	228528	5.31	172039	4.00
2010	4335182	308734	7.12	204612	4.72
2011	4401352	326649	7.42	203771	4.63
2012	4447165	301335	6.78	209793	4.72
2013	4495473	292178	6.50	295301	6.57

Trucks

As with passenger cars, data is available from Swedish Motor Vehicle Inspection company (Bilprovningen 2014) and transport analysis (Trafikanalys 2014). It should be noted that the data is split between light trucks which has a weight of 3500 kg or less and heavy trucks which has a weight above 3500 kg.

Figure 6 Average kilometers driven in km by light and heavy trucks, by year 2003-2013. Data from Trafikanalys.

Table 2 Light trucks turnover rates, weight -3500. Mean values of new registrations and deregistrations. Data from Trafikanalys.

	Total number of registered light trucks	New registrations		Deregistrations	
Year		Number	%	Number	%
2003	346405	30342	8.76	100 966	29.15
2004	364505	33547	9.20	106 933	29.34
2005	384776	37980	9.87	114 792	29.83
2006	401111	41264	10.29	121 146	30.20
2007	423920	45861	10.82	126 871	29.93
2008	430887	40404	9.38	146 071	33.90
2009	436333	28264	6.48	153 615	35.21
2010	447518	38750	8.66	162 245	36.25
2011	467533	47298	10.12	170 688	36.51
2012	477094	40168	8.42	179 732	37.67
2013	486052	38551	7.93	173 684	35.73

Table 3 Heavy trucks turnover rates, weight 3501- kg. Mean values of new registrations and deregistrations. Data from Trafikanalys.

	Total	New Registrations		Deregistrations	
Year		Number	%	Number	%
2003	75156	5619	7.48	44 584	59.32
2004	75480	5983	7.93	45 661	60.49
2005	76385	6657	8.72	46 652	61.07
2006	78683	6999	8.90	46 175	58.68
2007	80165	7644	9.54	46 903	58.51
2008	79312	7612	9.60	50 264	63.38
2009	78243	5966	7.62	52 089	66.57
2010	78923	5426	6.88	50 089	63.47
2011	80739	6775	8.39	50 332	62.34
2012	79727	6141	7.70	52 260	65.55
2013	79130	5712	7.22	47 963	60.61

Table 4 Light trucks in use by fuel, by year 2004-2013. Data from Trafikanalys.

Year	Gasoline	Diesel	Electric	Electric/ Electric hybrid	Ethanol / Ethanol hybrid	Gas / Gas hybrid	Others	Totalt
2004	147545	216033	263	0	34	265	365	364505
2005	138436	245229	241	0	106	637	127	384776
2006	127627	271744	207	0	224	1240	69	401111
2007	117927	303451	188	0	412	1879	63	423920
2008	106713	320497	156	0	669	2779	73	430887
2009	98553	332750	152	1	1066	3743	68	436333
2010	89068	352060	133	9	1424	4757	67	447518
2011	81687	378520	115	24	1583	5538	66	467533
2012	73530	395248	366	31	1758	6102	59	477094
2013	66583	410568	548	38	1788	6470	57	486052

Table 5 Heavy trucks in use by fuel, by year 2004-2013. Data from Trafikanalys.

Year	Gasoline	Diesel	Electric	Electric / Electric hybrid	Ethanol / Ethanol hybrid	Gas / Gas hybrid	Others	Totalt
2004	1674	73547	2	0	3	113	141	75480
2005	1656	74439	0	0	2	192	96	76385
2006	1587	76750	0	0	3	255	88	78683
2007	1506	78267	1	0	3	299	89	80165
2008	1428	77462	0	2	2	337	81	79312
2009	1370	76395	0	2	1	403	72	78243
2010	1270	77099	0	1	8	484	61	78923
2011	1239	78865	0	2	20	554	59	80739
2012	1196	77801	0	8	30	639	53	79727
2013	1139	77141	0	18	33	755	44	79130

Table 6 Average kilometers driven in km by light and heavy trucks, by year 2003-2013. Data from Trafikanalys.

	Light trucks	Heavy Trucks
Year	Km	Km
2003	13611	43354
2004	13762	43769
2005	14181	44668
2006	14289	45481
2007	14580	46480
2008	14820	45870
2009	14621	42918
2010	14418	42821
2011	14570	44310
2012	14379	42127
2013	14182	41561

Aviation

Data on domestic transportation as well as freight and mail transports are available from transport analysis (Trafikanalys 2014).

Year	Passenger- km	Vehicular traffic- km	Tonne- km
	Domestic	Domestic	Domestic
2006	3 290 032	52 429	-
2007	3 248 234	50 323	-
2008	3 233 405	50 593	8 692
2009	2 885 628	47 864	7 051
2010	2 979 230	47 254	6 679
2011	3 353 628	51 099	6 509
2012	3 395 870	49 069	6 267
2013	3 418 311	48 967	5 951

Table 7 Number of passenger-km, vehicular traffic-km and tonne-km (mail and freight) in domestic traffic 2006-2013, thousands Data from Trafikanalys

Maritime transports

Data on the Swedish vessels and ports are available from transport analysis (Trafikanalys 2014).

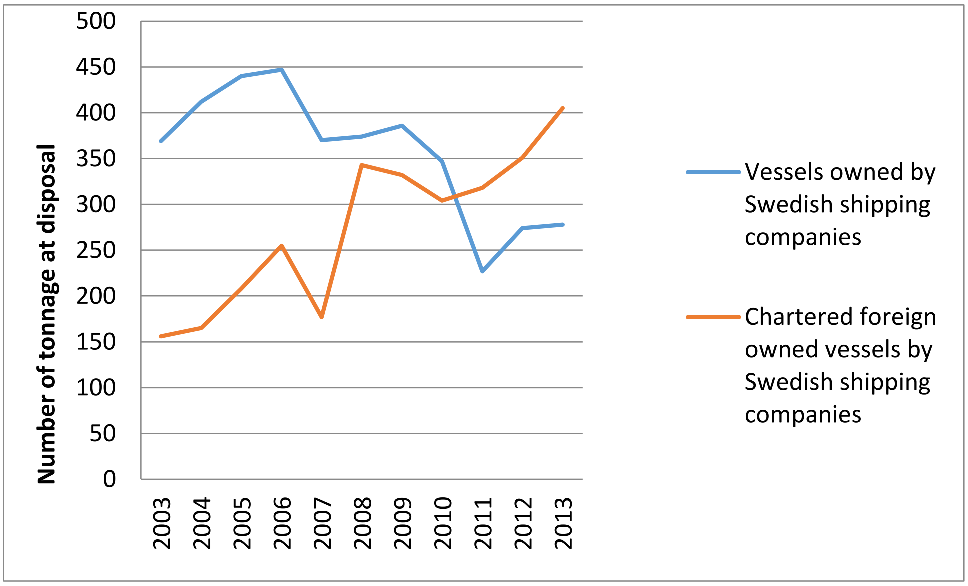

Figure 7 Number of tonnage at disposal for Swedish shipping companies both owned by Swedish companies and chartered from foreign shipping companies, vessels with gross tonnage of 100 and above Data from Trafikanalys

Prices

Data on fuel prices, fuel taxes, fuel consumption, and number of gas station are available at the Swedish Petroleum & Biofuel institute (Svenska petroleum och biodrivmedel institutet 2014).

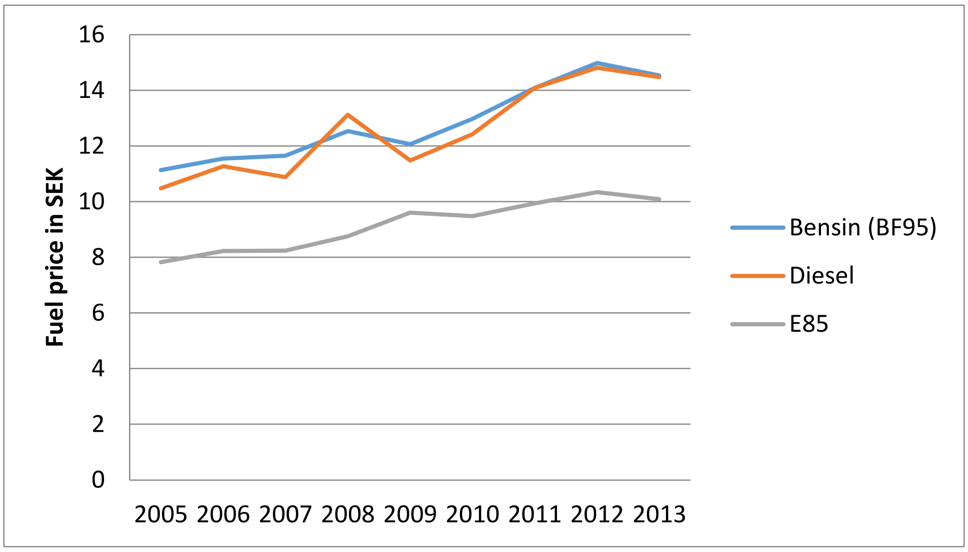

Figure 8 Fuel price in SEK from years 2005-2013. Data from Svenska petroleum och biodrivmedel institutet.

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Appendix B. Transport planners' views on rebound effects and questionnaire.

Transport planners' views on rebound effects

Author: Joanna Dickinson

Background and methods

Interviews were conducted with two transport planners as a pilot study. The aim was to capture transport planners' views on rebound effects in transport planning.
The interviews were carried out as semi-structured interviews, i.e. based on a questionnaire and with the possibility for open responses. The questionnaire used in the interviews was based on issues that were identified as interesting in the literature overview. The questionnaire in full is provided below.

Issues raised during the literature review concerned the knowledge on energy efficiency, energy efficiency and rebound effects relating to transport that is available in the strategic planning of the transport system. Other issues concerned how the interviewees' organisations, as well as other parties they interact with in the planning process, take into account these issues. Of particular interest was whether or not transport planning is working actively to contribute to national or other objectives which relate to energy efficiency, whether these objectives are measurable, and to what extent energy consumption, energy efficiency and rebound effects are taken into account when measures are being prioritised in transport planning.

Other issues in the interviews relate to the decision-making support and planning tools that are available in transport planning, and whether these take into account and help counteract rebound effects from investments in increased road capacity. Other issues covered in the interviews were whether there are barriers or conflicting objectives in the planning related to reduced energy consumption in the transport system, in particular when it comes to avoid rebound effects, and what would make it easier to avoid rebound effects for energy consumption in transport planning.

Two respondents were selected on the criteria that they have qualified experience of regional planning of the transport system in the Stockholm region, with the focus on road and rail transport, as well as insights into the local and national transport planning level. They also have experience of the newly introduced reformed planning process for the transport system in strategic early planning stages, and of measures and instruments to promote sustainable travel. It was therefore considered relevant to survey their views on rebound effects, as well as their experience of how rebound effects are illustrated and taken into account in the strategic planning of the transport system. The interviews were conducted in May and June 2014.

Results and discussion

The literature review revealed the existence of a large number of studies on rebound effects when it comes to increased energy efficiency in vehicles. However, the link between planning of the transport system and rebound effects associated with energy efficiency is covered to a significantly lower level in the available literature.

With regard to this, supplementary interviews were conducted with transport planners. The aim was to capture two transport planners' views on rebound effects in transport planning. In the interviews, it was found that the outcome of CBA prevails as the basis for decision making regarding priorities in planning of the road and rail transport system. If an investment is found as economically viable according to a CBA, a rebound effect which means increased energy consumption from increased travel is regarded as an increase in consumption that is desirable and reasonable - *"a greater prosperity we can say"*.

Rebound effects in the form of increased travelled mileage in road traffic generated by increased capacity in the transport system are something that planners are aware of. When an investment in road infrastructure is made and leads to increased congestion, an assessment is made of what the investment provides in terms of real capacity increase. Then rebound effects are taken into account in the form of induced traffic. Nevertheless, this is not necessarily considered to be negative according to one respondent.

There are targets for energy efficiency at the national level. Both interviewees stated, however, that energy efficiency is not perceived as an objective that is prioritised in the transport planning system. Energy efficiency does not constitute any actual *"point on the agenda"* so far in the planning process, as one respondent puts it: "*There are political objectives around this issue, but it would be necessary to simply formulate a climate scenario which should be a planning scenario for us to work with, where we meet the various objectives. This is what would be needed for us to be able to handle the matter fully. Such a priority of this issue has not been added, though. We have discussed this issue internally and see it as an important issue which we would be happy to work with, but our organization's approach is not such today."*

The second respondent also stated that the national objective for increased energy efficiency is not a clear priority in the everyday work with transport planning*: "It has always been such a horizontal objective for our work… making it rather diffuse."* This respondent's organisation works with objectives for increased energy efficiency in other sectors, such as housing, but energy efficiency is not taken into account as clearly in transport planning: *"...It is not a question that we're talking about, I say."* Within the organisation of this respondent, it is considered desirable to work more with mobility management towards less transport demand and increased travel shares with less energy-consuming transport modes than private car, and not only during the construction phase of new roads, which is often the case in the Stockholm region. *"It is very contradictory - sustainable mobility is promoted during the construction of road infrastructure, but later a brand new highway is ready - what signals does this send?"*

One interviewee stated that their own organisation is active in projects which aim to promote cars that are more energy-efficient, for example, by infrastructure for loading electricity vehicles, as well as the development of unmanned vehicles. The interviewee claimed that this is important to prevent an increase in energy consumption from increased road traffic, and that this is even a prerequisite to reach environmental objectives, including those addressing energy efficiency in transport.

More energy-efficient transport and reducing GHG emissions was indicated by both respondents as a reason for maintaining a high proportion of public transport travel share. Planning the transport system so that public transport is competitive in relation to the private car is considered important in transport planning in the Stockholm region. However, this is

not a stated objective, according to one of the interviewees. The second interviewee underlined the importance of choosing energy-efficient transport modes: *"I think that more energy efficient transport is not just a question of more energy efficient vehicles, but that it actually might be about traveling in a more energy-efficient way, by public transport and so. And we are working a lot to promote that people should bicycle more etc. This goes hand in hand with a lot of other objectives of an attractive city planning, public health, etc."*
In the planning of the transport system, models are used to make traffic forecasts, as a basis for the calculations of socio-economic viability in CBA. For large road investments, according to one respondent it is possible to describe rebound effects from induced road traffic that are a result of the investments. However, rebound effects leading to increased road transport mileage do not constitute a decisive criterion for prioritising measures in the transport system. On the contrary, increased road traffic is considered positive, if the CBA gives a positive outcome. *"In fact I believe that it is not so important. This is due to the fact that, as I have described, we have other parameters to follow to get it right. So we should not focus on rebound effects as a parameter. We should not analyze rebound effects and sort measures based on them."* The respondent stated that when the CBA shows a high level of profitability, depending mainly on reduced travel time and increased road safety, the measures might still be justifiable: *"... rebound effects means useful traffic that occurs when we create road capacity. This is how I look at the concept."*

The second interviewee stated that energy efficiency is not a factor that is taken into account as a measurable objective in the work with transport planning. This respondent believed that clearer indicators need to be developed and was critical of the models that are used to make traffic forecasts and to calculate socio-economic viability of infrastructure. One main reason is that the supporting documents are old and based on travel surveys of how people travelled in the 1980s and 1990s. The travel surveys at hand are thus based on completely other values than travellers of today. *"So I think that it is very misleading, what is profitable… We have, of course, old methods to make our plans ... it is, of course, a general problem which makes it more difficult to build sustainable, as it is so freaking profitable to continue to build roads."* The respondent did not consider that forecast models manage to count the effects in the form of increased traffic as a result of land use exploitation.

On the question of how the planning deliverables would be able to better highlight rebound effects of increased road capacity, one respondent stated that the CBA should be adjusted so that measures which mean negative environmental impact become less socio-economic viable. There is also a need for updated travel surveys in order to capture today's travel patterns of the population. One respondent considered that there is good knowledge generally for example about energy efficiency in transport, and that there are good planning tools at hand today, but that it is more a matter of getting a paradigm shift to bring about planning based on the objectives to be achieved.

Strategic plans, for example for cycling and for the development of the region, were mentioned as other decision support in transport planning, besides traffic forecasts and CBA. Measures and instruments mentioned that could counteract rebound effects in the planning of the transport system were congestion charges, parking policy and traffic management, in terms of strangling or turning off admission to highways when there is too much congestion. Even traffic jams can themselves be regarded as a kind of instrument to reduce rebound effects, as they reduce demand for road traffic. One respondent pointed out that within mobility management, there are examples of measures with good effect to contribute to more energy-efficient transport, and which do not involve large investment costs. One example that was mentioned is that one of the municipalities in the Stockholm region has differentiated school starting times and as a result managed to reduce traffic jams on the road network from the municipality. Freight transport was considered by one respondent to have good potential to improve energy efficiency.

In the interaction of the various actors in the county in transport planning, according to the respondents energy efficiency of transport is discussed, but only to a small extent taken into account in the decisions. Energy consumption, as well as rebound effects, are parts of the deliverables for decision making in the transport planning process but are not factors that are decisive.

As regards the question whether the respondents see obstacles or conflicting objectives to reduce energy consumption and avoid rebound effects in the transport system with the focus on planning, one respondent said that there can be a clash between energy efficiency and other objectives for transport planning, but that it does not really constitute a conflict. *"It depends... There are a number of different objective parameters, and this is one of several. "* One of the respondents pointed out political agreements on transport investments taken in the region as major obstacles for achieving more energy-efficient transport and avoiding rebound effects. These agreements contain maps showing prospective road investments, likely to generate large increases in travelled mileage by car. The maps create expectations of coming infrastructure investments among municipalities in the region.

On the question of the planning or decision-making level at which the responsibility for achieving more energy-efficient transport lies, one respondent stated that the objective of energy efficiency needs to be upgraded to be a priority in transport planning:
"... It must permeate the entire system in this case, the whole planning system. Then we can get to other results. ... One can't give priority to all objective parameters, so you need to do the priority from top to bottom – if so, it would be possible to reach other results."
The other respondent also believed that the main problem associated with avoiding rebound effects and increasing energy efficiency in transport is that transport planning needs to be aimed at reaching objectives to a much higher degree than today and that objectives for reduced climate impact and increased energy efficiency need to be lifted as a priority:
"The biggest problem is that we do not plan towards objectives. If there was a prioritized list of objectives, it would be much easier to plan in order to achieve them."

Frågemall för intervjufrågor (Questionnaire)

Av: Joanna Dickinson

Text med kursiv text är endast avsedd för intervjuaren.

Anvisningar för intervjuaren

- *Intervjufrågorna kan tas i tur och ordning, men det är inte nödvändigt. Utifrån hur samtalet utvecklas, kan ordningen på frågorna justeras, bara alla frågorna omfattas.*
- *Prata inte för mycket själv.*
- *Undvik att ”fylla i” svaren åt respondenten.*
- *Använd gärna ljudinspelning, då det underlättar att du inte missar något och gör dig mer fokuserad på samtalet i sig. Om du vill spela in intervjun, be om intervjupersonens tillstånd. Ge i så fall intervjupersonen ett skriftligt löfte om anonymitet som kommer att undertecknas. Berätta för intervjupersonen att inspelningen kan avbrytas när som helst och att rapporten inte kommer att innehålla några hänvisningar till en specifik person.*
- *Kom ihåg att följa upp frågor, be om motiv etc.*

Introduktion

Inleda med att berätta vem jag är och vad forskningsprojektet handlar om, vad projektet syftar till och hur resultaten ska användas (och publiceras).

Jag heter xx och arbetar på VTI, bland annat med ett projekt finansierat av Energimyndigheten.
Projektet innebär att kartlägga rekyleffekter i Sveriges transportsystem och uppskatta deras betydelse för energieffektivisering inom Sveriges transportsektor, och under vilka förutsättningar som rekyleffekter uppstår.
Rekyleffekt för energieffektivisering innebär att man genomför en åtgärd som syftar till att spara energi, men att den sparade andelen energi leder till ökad energikonsumtion, så att den faktiska energieffektiviseringen/besparingen blir övervärderad eller okänd. En del av energibesparingen ”äts upp” delvis, i större eller mindre grad.
Den här studien ska ge en djupare förståelse för olika typer av rekyleffekter i transportsektorn, och hur dessa ser ut för olika typer av styrmedel och andra åtgärder.
Syftet är att öka kunskapen om rekyleffekter så att åtgärder för att göra transporterna energieffektivare, inte äts upp av rekyleffekter. Projektet ska ge vägledning om vilka åtgärder och styrmedel som är mest effektiva för att nå målen om energieffektivare transporter samt begränsad klimatpåverkan, vilket är nära sammankopplat till effektivare energianvändning.
Vi önskar därför intervjua ett urval experter inom transportplanering.
Du har valts ut därför att du har en mycket god inblick i regional planering av transportsystemet, med koppling till den nationella och även lokala nivån. Du har också erfarenheter av den nya planeringsprocessen i åtgärdsval i tidiga skeden liksom av åtgärder för att främja hållbart resande. Vi skulle vilja få ta del av dina åsikter och erfarenheter som expert inom dessa områden.
Svaren kommer att användas som underlag för projektrapporten, men utan att vi explicit anger namn på intervjupersoner eller vem som sagt vad. Citat kan vara informativa, men då kan det bara stå ”planerare” t ex. *Informera om att om det är någon respondent som önskar vara helt anonym, så kommer alla att få bli det (och alltså inte nämnas ens i förordet).*
Informera om att efter intervjun kommer respondenten få en utskrift av intervjun för avstämning. ”Har vi uppfattat detta rätt? Är det ngt du vill tillägga, eller förtydliga?”
Svara utifrån din egen professionella synvinkel, inte organisationens.
Vi kommer som jag nämnde att avkoda svaren, som alltså inte kommer att kunna härledas till en specifik person. Får jag spela in?
(Sätt på diktafonen)

……………………………………………………………………………………………………

Bakgrundsfrågor

(Dagens datum)
(Den intervjuades namn)

1. Arbetsplats (enhet) och roll i organisationen?
2. Hur länge har du varit anställd i denna organisation?
3. Hur länge har du haft nuvarande befattning?
4. Vilken utbildning har du?

……………………………………………………………………………………………………

Projektrelaterade frågor:

1. Generellt, vilken kunskap har du om energieffektivitet när det gäller transporter?
   a. Från utbildningen? Teoretiskt?
   b. i det dagliga arbetet?

2. Har din organisation någon åsikt om energieffektivitet när det gäller transporter? *(Hur?)*

3. Har din organisation någon åsikt om rekyleffekter när det gäller energieffektiva transporter? *(Är detta en fråga som diskuteras i organisationen och verksamheten?)*

4. På vilket sätt är frågan om energieffektivare transporter aktuell i ditt arbete? Finns det målsättningar för er verksamhet som rör detta?
   (Direkt, eller indirekt via andra mål/inriktningar?) Mätbara?

   a. Finns denna typ av mål för energieffektivare transporter indirekt i andra styr-/policydokument eller planer med koppling till er verksamhet?

5. Hur långt har din organisation kommit med att nå sådana uppsatta mål för energieffektivare transporter (direkt eller indirekt?)

6. Vem har ansvaret (i teorin och i praktiken) inom din organisation för planering, beslut, genomförande och uppföljning för att kunna styra mot energieffektivare transporter, och de andra mål som har koppling till detta?
   (Finns det ett utpekat ansvar? Vem driver arbetet? Är det någon skillnad mellan utpekat ansvar och ansvar i praktiken?)

7. Är energieffektivare transporter en viktig fråga för ditt arbete med transportplanering? Hur?

8. Har du i detta arbete stött på termen ”rekyleffekter” i samband med energieffektivitet? I vilket sammanhang då?

9. Vilket kunskaps- och beslutsunderlag och vilka planeringsverktyg finns för ert arbete med transportplanering?

a. Känner du att de ger stöd för att beakta och motverka rekyleffekter i form av ökat trafikarbete eller ökad energiförbrukning av transporter på andra sätt?
b. Om inte, hur tänker du att de kan förbättras?

(Kunskapsunderlag och verktyg kan vara av mycket olika slag, t ex prognoser, scenarier, utredningar, modeller, karteringar, medier, allmänheten. Användbarhet? Utvecklingsbehov?)

10. I det arbete du och din organisation bedriver med transportplanering, görs det, eller har det gjorts, analyser av energiåtgång? Av energieffektivitet? Av rekyleffekter?

11. I vad mån beaktas energiförbrukning i dessa planer? I vad mån beaktas energieffektivisering? Rekyleffekter?

12. I ditt arbete, hur ser du på rekyleffekters betydelse när det gäller energieffektivare transporter?

    a. Har du någon uppfattning om de har stor eller liten betydelse för att nå de mål som verksamheten ska bidra till att nå?)

    b. Hur tänker du att man i transportplanering kan bidra till att undvika rekyleffekter när det gäller energieffektivitet för transporter?

    c. Har du någon uppfattning om vilka åtgärder som har större eller mindre betydelse för att undvika rekyleffekter?

13. Vilken samverkan har du/din organisation med andra aktörer i arbetet med planering av transportsystemet?

14. Hur diskuteras och vägs energieffektivisering in i denna samverkan när beslutsunderlag tas fram?

15. Hur vägs rekyleffekter för energieffektivare transporter in vid beslut om inriktning på planering av transportsystemet, t.ex. vid prioritering av åtgärder?

16. Vad i planeringen skulle göra det lättare att undvika rekyleffekter?

17. Ser du hinder eller målkonflikter i arbetet med att minska energiförbrukningen i transportsystemet, och särskilt när det gäller att undvika rekyleffekter?
    (Målkonflikter (kommunala/regionala utvecklingsmål, ekonomiska mål, trafikpolitiska mål, miljökvalitetsmål...)

18. På vilken planerings- eller beslutsnivå anser du att ansvaret för att uppnå energieffektivare transporter ligger? Utveckla!
    (Politisk, tjänstemanna-, lokal/regional/nationell...)

19. På vilken planerings- eller beslutsnivå anser du att ansvaret för att motverka rekyleffekter när det gäller energieffektivare transporter ligger? Utveckla!

(Politisk, tjänstemanna-, lokal/regional/nationell…)

20. Några fler reflektioner? Är det något du vill tillägga?

Tacka intervjupersonen för medverkan och nämn igen kort att intervjumaterialet kommer att användas i anonymiserad form och i en projektrapport.

www.vti.se
vti@vti.se

VTI, Statens väg- och transportforskningsinstitut, är ett oberoende och internationellt framstående forskningsinstitut inom transportsektorn. Huvuduppgiften är att bedriva forskning och utveckling kring infrastruktur, trafik och transporter. Kvalitetssystemet och miljöledningssystemet är ISO-certifierat enligt ISO 9001 respektive 14001. Vissa provningsmetoder är dessutom ackrediterade av Swedac. VTI har omkring 200 medarbetare och finns i Linköping (huvudkontor), Stockholm, Göteborg, Borlänge och Lund.

The Swedish National Road and Transport Research Institute (VTI), is an independent and internationally prominent research institute in the transport sector. Its principal task is to conduct research and development related to infrastructure, traffic and transport. The institute holds the quality management systems certificate ISO 9001 and the environmental management systems certificate ISO 14001. Some of its test methods are also certified by Swedac. VTI has about 200 employees and is located in Linköping (head office), Stockholm, Gothenburg, Borlänge and Lund.

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