

Department of Built Environment

Rebound effects projected onto carbon footprints

Implications for climate change mitigation in the built environment

Juudit Ottelin



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Climate change mitigation in the built environment encompasses various mitigation measures, such as energy efficient buildings, spatial planning instruments and other policies targeting the emissions resulting from transport. However, studies on the impacts of these measures typically only focus on a single emission source, such as housing energy or transport. The thesis enlightens, why the focus on the targeted emissions alone is misleading in many cases. The key concept of the thesis is the rebound effect. While mitigation measures often reduce the targeted emissions, they have unintended consequences due to shifts in consumption. These unintended consequences are called rebound effect.

The thesis contributes to carbon footprint research in the built environment and supports the earlier findings that urban structure has a weak or even statistically insignificant connection to total carbon footprints, despite having a relatively strong effect on driving-related emissions. The thesis explains this phenomenon via the rebound effects for reduced car ownership and driving, but also by means of other issues covered in the thesis. In Finland, which is the geographical scope of the thesis, the benefits of intra-household sharing are stronger in suburban areas than in inner urban areas, which alleviates the harmful effects of urban sprawl. Furthermore, new energy efficient housing has reduced carbon footprints in outer urban areas but not in inner urban areas. While the effect of urban structure appears low, direct reduction of driving, energy efficient housing and the sharing of greenhouse gas intensive goods and services seem to reduce carbon footprints significantly.

The thesis aims to bridge the gap between studies on theoretical rebound effects and studies on empirical carbon footprints within the context of the built environment. Rebound effects are usually studied with econometric modelling, whereas carbon footprint studies are based on the real expenditure of consumers. A carbon footprint-based definition for rebound effect is presented as the theoretical implication of the thesis. This graphic presentation could be used for rigorous empirical testing of rebound theories by using carbon footprints when longitudinal data are available. In practice, the thesis demonstrates the ways in which cross-sectional carbon footprints can be employed to estimate probable rebound effects.

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Tekijä

Juudit Ottelin

Väitöskirjan nimi

Kulutuksen kimmoisuusvaikutusten heijastuminen hiilijalanjälkiin ja merkitys ilmastomuutoksen hillinnälle rakennetussa ympäristössä

Julkaisija Insinööritieteiden korkeakoulu**Yksikkö** Rakennetun ympäristön laitos**Sarja** Aalto University publication series DOCTORAL DISSERTATIONS 219/2016**Tutkimusala** Kiinteistöliiketoiminta**Väitöspäivä** 11.11.2016**Julkaisuluvan myöntämispäivä** 31.08.2016**Kieli** Englanti **Monografia** **Artikkeliväitöskirja** **Esseeväitöskirja****Tiivistelmä**

Rakennetun ympäristön aiheuttamia kasvihuonekaasupäästöjä pyritään vähentämään monilla keinoilla, kuten energiatehokkaalla rakentamisella ja kaupunki- ja liikennesuunnittelulla. Keinojen toimivuutta mitataan yleensä keskittymällä yhteen päästölähteeseen, esimerkiksi asumisen energiaan tai liikenteen päästöihin. Käsillä oleva tutkimus avaa tällaiseen lähestymistapaan liittyviä ongelmia. Tutkimuksen pääkäsite on kulutuksen kimmoisuusvaikutus (rebound effect). Vaikka ilmastonhillintätoimenpiteet usein vähentävät niitä päästöjä, joihin ne kohdistuvat, ne muuttavat samalla kulutuksen allokoitua, mikä voi johtaa yllättäviin seurauksiin. Tätä kutsutaan kulutuksen kimmoisuusvaikutukseksi.

Tutkimus jatkaa rakennetun ympäristön hiilijalanjälkitutkimusta, ja tukee aiempaa löydöstä kaupunkirakenteen heikosta yhteydestä kokonaiishiilijalanjälkiin, vaikka sen vaikutus autoilun päästöihin on merkittävä. Tutkimus selittää ilmiötä erityisesti autoilun ja auton omistuksen vähentämiseen liittyvillä kulutuksen kimmoisuusvaikutuksilla, mutta myös muilla tutkimuksen kattamilla aihealueilla. Kotitalouksien sisäinen resurssien jakaminen pienentää hiilijalanjälkiä enemmän ulommilla kaupunkiviyöhykkeillä kuin kaupunki-keskustoissa. Lisäksi energiatehokas asuminen on pienentänyt hiilijalanjälkiä pientaloalueilla, mutta ei sisimmällä kaupunkiviyöhykkeellä. Vaikka kaupunkirakenteen vaikutus näyttäytyy tutkimuksessa heikkona, autoilun suora vähentäminen, energiatehokkaat rakennukset ja hiili-intensiivisten tuotteiden ja palveluiden jakaminen näyttäisivät pienentävän hiilijalanjälkiä merkittävästi.

Tutkimus tuo teoreettista tutkimusta kulutuksen kimmoisuusvaikutuksista ja empiiristä hiilijalanjälkitutkimusta rakennetussa ympäristössä lähemmäksi toisiaan. Kimmoisuusvaikutuksia tutkitaan perinteisesti ekonometrisella mallinnuksella. Hiilijalanjälki-tutkimus puolestaan nojaa todelliseen kulutukseen. Tutkimuksen teoreettisena ja metodologisena johtopäätöksenä esitetään hiilijalanjälkiin perustuva määritelmä kulutuksen kimmoisuusvaikutukselle. Tätä graafista esitystä voi käyttää kimmoisuusvaikutusteorioiden empiiriseen testaukseen, jos käytettävissä on pitkittäisdataa. Käytännössä tutkimus havainnollistaa, kuinka myös tyypillistä kulutustutkimus-dataa yhdessä ajanpisteessä voidaan käyttää kimmoisuusvaikutusten suurpiirteiseen arviointiin.

Avainsanat hiilijalanjälki, kulutuksen kimmoisuusvaikutus, panos-tuotos analyysi, elinkaariarviointi, kaupunkirakenne, rakennettu ympäristö, kasvihuonekaasupäästö

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Mótvægisáðgerðir loftslagsbreytinga sem viðkoma hinu byggða umhverfi innifela orkusparandi byggingar, breyttar skipulagsáætlanir auk annarra áðgerða sem draga úr losun gróðurhúsalofttegunda frá samgöngum. Árangur og áhrif mótvægisáðgerða miða hins vegar oftast við eina uppsprettu losunar, t.d. húshitun eða samgöngur, óháð öðrum uppsprettum. Þessi rannsókn sýnir hvernig slík nálgun getur leitt til villandi niðurstaðna í mörgum tilfellum. Aðal viðfangsefni þessarar ritgerðar eru hliðaráhrif mótvægisáðgerða. Þó tiltekna mótvægisáðgerðir dragi úr losun gróðurhúsalofttegunda í þeim geira þar sem þeim er beitt, þá geta þær haft neikvæð hliðaráhrif (e. rebound effects) vegna hliðrunar á neyslu.

Ritgerðin er framlag til rannsókna á kolefnisspori hins byggða umhverfis. Niðurstöður ritgerðarinnar styðja fyrri rannsóknir sem sýna að byggðamynstur hafi veika, eða jafnvel tölfræðilega ómarktæka, fylgni við heildar kolefnisspor, þrátt fyrir að hafa tiltölulega mikil áhrif á losun gróðurhúsalofttegunda vegna aksturs bifreiða. Í ritgerðinni er þetta útskýrt með greiningu á hliðaráhrifum vegna minni bifreiðaeignar og minni aksturs, auk annarra áhrifa sem fjallað er um í ritgerðinni. Í Finlandi, sem er rannsóknarsvið ritgerðarinnar, eru Jákvæð jákvæð samlegðaráhrif innan heimila eru meiri í úthverfum en miðborgum, sem dregur úr neikvæðum áhrifum strjállar byggðar á kolefnisspor. Enn fremur, þá hafa nýjar og hagkvæmari byggingar, sem nýta orku betur, dregið úr kolefnisspori úthverfa en ekki miðbæjarkjarna. Þrátt fyrir að áhrif byggðamynsturs séu í sjálfu sér lítil þá virðast minni akstur bifreiða, orkusparandi húsnæði og samnýting á vörum og þjónustu sem losa gróðurhúsalofttegundir hafa marktæk áhrif til að draga úr kolefnisspori byggðs umhverfis.

Í ritgerðinni er leitast við að brúa bilið á milli fræðilegra rannsókna á hliðaráhrifum og reynslurannsókna á kolefnissporum innan hins byggða umhverfis. Hliðaráhrif eru yfirleitt rannsökuð með aðferðum hagrannsókna þar sem kolefnisspor eru tengd raunverulegum útgjöldum neytenda. Hluti af fræðilegu framlagi þessarar rannsóknar er skilgreining á hliðaráhrifum sem byggir á kolefnisspori. Hægt er að nota skilgreininguna til ítarlegri rannsókna á hliðaráhrifum þegar gögn eru til sem spanna mörg tímabil. Ritgerðin sýnir einnig hvernig má nota kolefnisspor, sem mæld eru á einum tímamarki, á hagnýtan hátt til að meta líkleg hliðaráhrif til lengri tíma.

Lykilorð kolefnisspor, hliðaráhrif, aðfanga- og afurðagreining, lífsferilsgreining, byggt umhverfi, byggðamynstur, losun gróðurhúsalofttegunda

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List of Abbreviations

CO ₂ -eq	CO ₂ -equivalent (GWP ₁₀₀)
EE IO analysis	environmentally extended input output analysis
EIO-LCA	economic input output life cycle assessment (synonym for EE IO analysis)
GHG	greenhouse gas
GWP ₁₀₀	global warming potential, 100-year time perspective
LCA	life cycle assessment
VKT	vehicle kilometres travelled

Terminology

Carbon footprint in the thesis means the total direct and indirect greenhouse gas (GHG) emissions caused by the consumption patterns of a person, household, city, nation or some other group of people during one year. The carbon footprints discussed in the thesis have been calculated with a hybrid life-cycle assessment (LCA), and their unit is CO₂-eq kg/year per capita. Carbon footprint literature refers in the thesis to the consumption-based GHG and energy requirement assessments using EE IO analysis. The term ‘carbon footprint’ is well-established in the EE IO analysis literature (Wiedmann 2009a). For a broader definition of ‘carbon footprint’, see Weidema et al. (2008).

Cross-sectional data means data that includes only one point in time. **Panel data** includes time series data for at least in two points in time, whereas **longitudinal data** includes data collected from the same units (e.g. households) during at least two points in time.

Direct emissions and **indirect emissions** have two separate definitions in the thesis based on how they are discussed in the relevant literature. Within the context of consumption-based carbon footprints, **direct emissions** refer to the emissions caused by energy (heat and electricity) and fuel consumption, including the upper-tier emissions from fuel production and distribution, etc. **Indirect emissions** mean the emissions caused by all other types of consumption (Lenzen et al. 2004; Shammin et al. 2010; Wiedenhofer et al. 2013). Within the context of the process LCA and production-based GHG accounting, **direct emissions** mean the direct emissions caused by the combustion of fuels (including heat and electricity production and transportation), industrial processes and waste. **Indirect emissions** mean the embedded emissions in products and services (Chávez & Ramaswami 2011).

EE IO analysis is a method developed by Wassily Leontief. It is based on input-output economics, also invented by Leontief. The input-output tables of an economy consist of monetary transaction matrices describing transactions between economic sectors. Each economic sector uses inputs to produce intermediate products (outputs that serve as inputs in other sectors) or final products and services (outputs). With environmental extension, pollution amounts or other environmental indicators are added to the matrices so that environmental

burdens and how to eliminate them can be analysed (Leontief 1970). EE IO analysis is a top-down method.

Hybrid LCA in the thesis refers to a life-cycle assessment that combines EE IO analysis and traditional process LCA (Suh et al. 2004).

Process LCA means traditional LCA studies that focus on the main processes causing environmental impacts (Suh et al. 2004). Process LCA is a bottom-up method.

Rebound effect means in general the unintended consequences of climate change mitigation measures (or other measures striving for sustainability) due to shifts in consumption (Lenzen & Dey 2002; Hertwich 2005; Druckman et al. 2011). It is usually defined as a percentage – for example, 20 % rebound means that 80 % of the expected GHG reduction is realized, and 20 % of the reduction is offset by the rebound effect. In the thesis, if not mentioned otherwise, rebound effect refers to both direct and indirect rebound effects in terms of GHG emissions; it does not include the economy-wide rebound effects. The terminology for rebound effects is discussed in more detail in Section 3.2.

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

Paper I

Ottelin, J., Heinonen, J. & Junnila, S. 2014, 'Greenhouse gas emissions from flying can offset the gain from reduced driving in dense urban areas', *Journal of Transport Geography*, vol. 41, pp. 1–9.

Paper II

Ottelin, J., Heinonen, J. & Junnila, S. 2015, 'New Energy Efficient Housing Has Reduced Carbon Footprints in Outer but Not in Inner Urban Areas', *Environmental Science & Technology*, vol. 49, no. 16, pp. 9574–9583.

Paper III

Ala-Mantila, S., Ottelin, J., Heinonen, J. & Junnila, S. 2016, 'To each their own? Greenhouse gas impacts of intra-household sharing in different urban zones', *Journal of Cleaner Production*, vol. 135, pp. 356–367.

Paper IV

Ottelin, J., Heinonen, J. & Junnila, S. 2016, 'Rebound effect for reduced car ownership and driving', chapter in a book: *Nordic Experiences of Sustainable Planning: Policy and Practice*, editor: Sigríður Kristjánsdóttir, Taylor & Francis Group, book series on Urban planning and environment. In press.

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Journal of Cleaner Production	3,84	1,59

Author's Contribution

Paper I: *Greenhouse gas emissions from flying can offset the gain from reduced driving in dense urban areas*

The author is responsible for initiating, executing and writing the paper. The co-authors provided advice, comments and suggestions.

Paper II: *New Energy Efficient Housing Has Reduced Carbon Footprints in Outer but Not in Inner Urban Areas*

The author is responsible for initiating, executing and writing the paper. The co-authors provided advice, comments and suggestions.

Paper III: *To each their own? Greenhouse gas impacts of intra-household sharing in different urban zones*

The author is responsible for the construction of the carbon footprint model used in the study and for writing the parts of the paper that describe the model. In addition, she has participated in the search for relevant literature and helped write the introduction.

Paper IV: *Rebound effect for reduced car ownership and driving*

The author is responsible for initiating, executing and writing the paper. The co-authors provided advice, comments and suggestions.

1. Introduction

I have never met a person whose aim it would be to damage the environment. If people were polled, ‘Should we save the planet for future generations?’, very few would answer no. The point at which we disagree is how it should be done. While sustainability has become a ubiquitous topic, at the same time talk about sustainability has become increasingly more complex, ambiguous and even contradictory. Too often we end up implicitly stating, ‘my way of living is the only correct way of living’. We easily notice when others are not making the same sustainable choices that we are making, but do we notice when others are making sustainable choices that we are not?

The thesis is a story about the fascinating and sometimes depressing carbon footprints of consumers in the built environment. The thesis illustrates via practical examples and empirical data how little people’s total carbon footprints differ when people who have adopted various climate change mitigation measures are compared to people who have not adopted such measures. It is a horror story about how our efforts seem to run into the sand; but it has hope too, since some mechanisms are found that do reduce people’s carbon footprints.

The key concept in the thesis is rebound effect (Lenzen & Dey 2002; Hertwich 2005; Druckman et al. 2011). Here, it means the unintended consequences of climate change mitigation measures due to shifts in consumption patterns. Carbon footprints can capture the rebound effects and this is what makes them interesting compared to other greenhouse gas (GHG) assessment methods. In a wider scope, rebound effects are related to all sustainable choices, not only climate change mitigation.

Basically, sustainable choices often save money (think, for example, of biking instead of driving). Intuitively, it seems like a good thing – a win-win situation. However, the money that is saved is ultimately spent on something else. Thus, the success or failure of a particular sustainable choice actually depends more on what people choose to spend their money on in the long run. The emissions that result from a new form of consumption, prompted by the money saved via the sustainable choice, are called the rebound effect. In the case of biking or driving, we should not compare the emissions directly; rather, we should include the monetary dimension. If driving costs €1000/year and biking €100/year, a fair comparison would be to assess the emissions caused by spending €1000. If a person chooses to drive, she or he would consume the total €1000. If they choose instead to bike, they would consume €100, and then be free to use €900 on something else. Ultimately, we would need to know what

the person spent that €900 on to adequately assess the overall emissions. Similarly, sustainable choices that require investments may have ‘negative’ rebound effects, that is to say, they may lead to additional GHG reductions due to the decreased consumption of other goods and services. The invested funds must be withdrawn from some other purposes. Carbon footprinting methods are founded in translating monetary expenditures to environmental impacts. This makes them ideal for studying the rebound effects.

Rebound effects are related both to the consumption choices of individuals and to the environmental policies of nations, cities and corporations. The focus of the thesis is on climate change mitigation measures in the built environment, but the results have wider significance regarding the rebound effects. The thesis provides insights for policymakers, researchers and consumers. If we just learn to understand the rebound effects, we can harness them for good use.

1.1 Climate change mitigation in the built environment

The context of the thesis is the built environment. The Oxford Dictionary defines the built environment as ‘*Man-made structures and facilities used to accommodate societies’ activities. Any enclosures, spaces, structures, and infrastructure formed to convert the natural environment into a habitable and useable area for the purpose of living, working, and playing*’ (Gorse et al. 2012). The built environment surrounds us everywhere, and it provides an excellent setting to study both behavioural change and technological solutions as climate change mitigation measures. In the thesis, mitigation measures stand for both climate change mitigation policies and measures that consumers can adopt. The focus of the thesis is at the policy level.

The research that makes up the thesis started from the field of transport research. A large body of literature demonstrates how high-density, mixed-use neighbourhoods with high accessibility and connectivity lead to reduced driving and increased walking (see, e.g. Badoe & Miller 2000; Crane 2000; Cao et al. 2009; Ewing & Cervero 2010; Naess 2012). This has led to environmental policies that emphasize the need to increase urban density and avoid urban sprawl (European Commission 2011; Van Stigt et al. 2013; Edenhofer et al. 2014). The thesis studies what happens when the system boundary is broadened to include air travel. There are a few previous travel studies presenting a positive correlation between the level of urbanity and long-distance travel (Brand & Preston 2010, Holz-Rau et al. 2014), and a few expenditure studies providing similar results on flying (Lenzen et al. 2004; Ornetzeder et al. 2008; Heinonen et al. 2013a, 2013b). The results of the thesis support the findings of these previous studies, and take the idea further by presenting a negative correlation between car ownership and the amount of flying.

Aside from transport research, several studies have also focused on the GHG emissions caused by human settlements from a broader perspective. Studies that examine the emissions from ground transport and housing energy provide similar conclusions as conventional transport research relating to the benefits of dense urban structure (Norman et al. 2006; Ewing & Rong 2008; Kennedy et

al. 2009; Glaeser & Kahn 2010; see also the review by Rickwood et al. 2008). However, there is an increasing amount of literature describing how a system boundary selection that only includes housing energy and ground transport may lead to biased conclusions about the impact of urban structure on GHG emissions (Lenzen et al. 2004; Lenzen et al. 2006; Baiocchi et al. 2010; Shammin et al. 2010; Minx et al. 2013; Wiedenhofer et al. 2013; Heinonen et al. 2013a, 2013b; Ala-Mantila et al. 2014). These studies on consumption-based carbon footprints and energy requirements in the built environment have found that the growth in other forms of consumption cancels out part or all of the emission reductions from driving and housing energy in densely populated areas. Consumption-based studies use expenditure to assess environmental pressure. Consumption-based GHG assessments are called carbon footprints.

The thesis contributes to carbon footprint research in the built environment and makes an effort to explain the equality of total carbon footprints in different urban structures, especially via the rebound effects for reduced car ownership, but also by means of other issues covered in the thesis. In addition, the urban-rural classification used here is more detailed than in previous carbon footprint studies and based on such variables as accessibility and distance from the city centre rather than municipal or other administrative boundaries.

Climate change mitigation in the built environment is not just limited to urban density policies. The thesis also examines new energy efficient housing and sharing of resources. In addition, the results related to reduced driving and car ownership have implications for other mitigation policies as well, such as car-pooling and energy efficient vehicles. One clear pattern arising from carbon footprint studies in general, and particularly the studies that make up the thesis, is the existence of rebound effects. The evolving theory on rebound effects can explain many of the otherwise surprising findings of the thesis.

Contemporary studies on rebound effect are generally based on econometric modelling. The rebound effects for mitigation measures targeting heating energy and personal transport have been broadly studied (e.g. Greening et al. 2000; Alfredsson 2004; Nässén & Holmberg 2009; Hens et al. 2010; Druckman et al. 2011; Thomas & Azevedo 2013a, 2013b; Chitnis et al. 2014). There are also some experimental studies providing evidence on rebound effects (see e.g. the review by Sorrell et al. 2009). However, the generally employed econometric rebound models are theoretical by nature and include several assumptions and uncertainties related to consumption behaviour. At the same time, carbon footprint studies dealing with the built environment are based on real, not modelled, consumer expenditures and disposable income. They often discuss rebound effects that seem to provide a plausible explanation for certain observations (Druckman & Jackson 2009; Wiedenhofer 2013; Heinonen et al. 2013a, 2013b). While the studies on rebound effects and carbon footprints partly overlap with one another, mostly they can be divided into two separate fields of research.

The thesis aims to bridge the gap between studies on theoretical rebound effects and studies on empirical carbon footprints within the context of the built environment. A carbon footprint-based definition for rebound effect is presented as the theoretical implication of the thesis. This graphic presentation

could be used for rigorous empirical testing of rebound theories by using carbon footprints when longitudinal data are available. In practice, the thesis demonstrates the ways in which cross-sectional carbon footprints can be employed to estimate probable rebound effects. It should be noted, however, that rebound theory is not the only possible explanation for the observations discussed in the thesis. Rebound theory is in the focus of the thesis, since it forms the common denominator for all of the mitigation measures studied here.

The results of the thesis suggest that the rebound effects for climate change mitigation measures in the built environment can vary from negative to very high, and thus they must be taken into account when the effectiveness of mitigation policies is evaluated. The finding regarding negative rebound effects implies that one major problem with many existing econometric rebound effect models is that they neglect capital costs, as suggested previously for example by Henly et al. (1988), Mizobuchi (2008), Nässén and Holmeberg (2009), Chitnis et al. (2013, 2014) and Font Vivanco et al. (2014, 2015).

The structure of the thesis is as follows. Section 1.2 discusses the research question, while Section 1.3 explains the scope of the thesis. Chapter 2 presents the methodology of carbon footprinting. Chapter 3 provides the theoretical foundation of the thesis. It includes a literature review of carbon footprints in the built environment and a shorter review on the concept of rebound effect. Chapter 4 describes the empirical contribution of the thesis, whereas Chapter 5 provides the final discussion, including the theoretical and methodological implications of the thesis, the implications of rebound effects for the mitigation measures studied here, general policy implications, an evaluation of the research and some suggestions for future research.

1.2 Research question

When the effectiveness of climate change mitigation measures in the built environment is assessed, it is often done by focusing on a single emission source, for example ground transport or heating energy. Such an assessment excludes the rebound effects, which leads to biased results. The aim of the thesis is to provide empirical studies on carbon footprints that illustrate the rebound effects for selected mitigation measures in the built environment. The research question of the thesis is as follows:

How does the allocation of expenditures and the resulting GHG emissions differ between a group that has not adopted (been affected by) the studied mitigation measure and another group that has adopted the measure?

The studied mitigation measures, or more generally, the studied variables include car ownership and the amount of driving, energy efficient housing and the sharing of resources. Also, all of these measures are connected to the urban structure and to density policies in urban planning. The measures represent

both individual choices (the choice to be car free, choices about residential location, etc.) and policy measures (urban density policies, energy efficiency policies, etc.) at a crude level. Thus, the phrasing ‘adopted the studied mitigation measure’ in the research question must be understood broadly. It refers to people who have actually adopted the measures and people who have been affected by climate change mitigation policies. Also, the reasons behind adopting the measures in question are unknown and may not include the intentional aim to reduce GHG emissions.

The question is important since it helps to answer, which sorts of mitigation measures work most effectively in the built environment, and which sorts of mitigation measures are likely to lead to high rebound effects on a large scale. The variation in the allocation of expenditures between the studied groups of people reflects the possible rebound effects for the studied mitigation measures. In other words, the thesis clarifies why mitigation measures often result in more modest emission reductions than expected. In the long term, an increased understanding of rebound effects will aid in efforts to tackle undesired rebounds and harness negative rebounds, which mean additional GHG reductions.

1.3 Scope of the thesis

The thesis consists of four peer-reviewed papers and the compilation. Each of the four papers study one or two variables representing mitigation measures in the built environment. Papers I and IV study car ownership and driving, while Paper II studies energy efficient housing and Paper III the sharing of resources. All of the papers include an urban structure variable, and each analyses the connections between urban density policies and other mitigation measures.

The studied mitigation measures have been chosen so that they cover both behavioural and technological solutions, and have a close connection to the built environment. Spatial planning instruments, energy efficient buildings and policies targeting the emissions from transport constitute some of the key climate change mitigation policies in the built environment according to the Fifth Assessment Report of Intergovernmental Panel on Climate Change (Edenhofer et al. 2014). They also represent important areas of concern in the EU’s climate policies (e.g. European Commission 2011). Sharing of resources is included, since carbon footprint (per capita) generally declines with increasing household size, due to sharing of living space and other resources within the household. This is a strong pattern, and raises the question of whether sharing could be used more widely – also between households – to reduce GHG emissions. The pattern is also connected to the built environment, as Paper III demonstrates. The list of the chosen mitigation measures is in no way exhaustive, and further research on other measures is warranted.

Figure 1 illustrates the connections between the studied variables (mitigation measures), the papers and the research question. It provides a short description of the contribution of each paper to the research question. It also presents the main implications of each paper with respect to possible rebound effects.

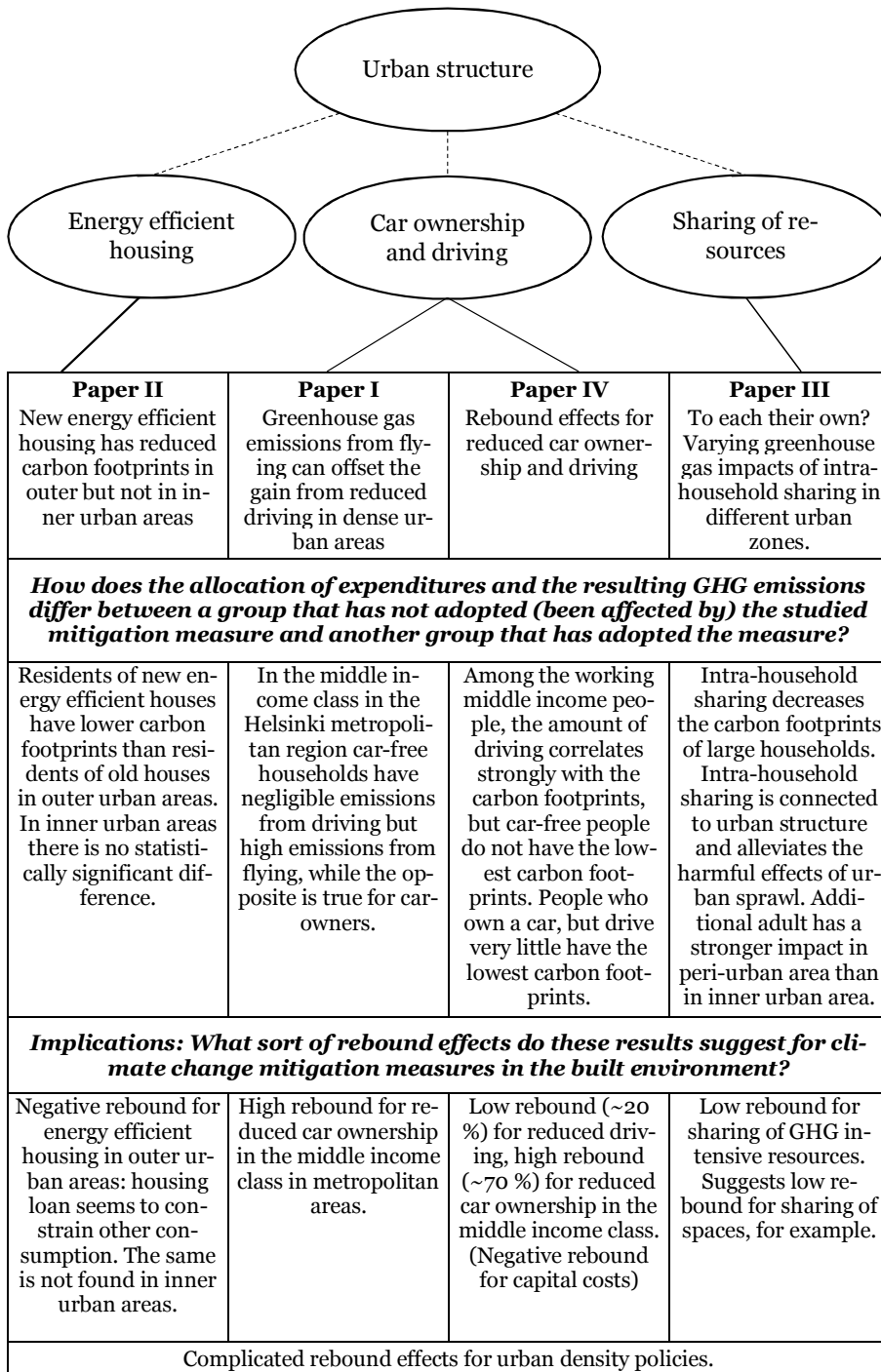


Figure 1. The connections between the studied variables (climate change mitigation measures), the papers and the research question, particularly the contribution of each paper to the research question and the main implications concerning rebound effects.

The research is based on descriptive quantitative analyses. Two datasets are used: the Finnish National Travel Survey 2010–2011 and Statistics Finland’s Household Budget Survey 2012. The total sample sizes consist of more than 10 000 persons and 3 500 households, respectively. Carbon footprints are assessed using the hybrid life-cycle assessment (LCA) method based on an environmentally extended economic input-output (EE IO) model. The employed statistical analyses include regression analyses and comparisons of the means.

The geographical scope of the thesis is the country of Finland. Papers I and IV cover all of Finland. Papers II and III focus on the urban areas and exclude the rural areas. They cover all urban areas in Finland. Helsinki, the capital, is studied separately in Paper III, whereas the Helsinki metropolitan region, which includes 19 municipalities, is studied separately in Paper I.

The thesis uses the urban-rural classification of the Finnish Environment Institute (Helminen et al. 2014) as the measure for urban structure in Papers II–IV. The urban-rural classification has been developed quite recently to replace the previous classification, which was based on municipal boundaries. The new urban-rural classification describes the inner urban-suburban-rural continuum, which also exists within cities. The classification is based on rich GIS data on population, labour, commute times, distance from a local centre, buildings, road networks and land use. The thesis uses the three urban classes, and the rural classes are combined to form one rural class (only included in Paper IV). The urban structure classes used in the thesis are as follows (Helminen et al. 2014):

1. *Inner urban area*: a compact and densely built area with continuous development, i.e. the central area of cities.
2. *Outer urban area*: a dense urban area extending from the boundary of the inner urban area to the outer edge of the continuously built area.
3. *Peri-urban area*: part of the intermediate zone between urban and rural, which is directly linked to an urban area.
4. *Rural area*

Since the classification is intended for national use, and since Finland is quite sparsely populated, these classes may not describe inner and suburban areas at an international level quite so well. For example, almost all of Helsinki falls into the inner urban area classification. Helsinki is the centre of the only metropolitan area with more than one million inhabitants in Finland. Overall, approximately 30% of the population in Finland lives in the inner urban areas, whereas 30% live in the outer urban areas, 10% in the peri-urban areas and 30% in the rural areas.

The unit of analysis in the thesis is carbon footprint per capita. Another possibility would be to use the carbon footprints of households, or some equivalence scale. Equivalence scales give different weightings for children and adults, for example. They are used in economics to yield a more representative income, for example. Figure 2 illustrates how the choice of the unit of analysis affects the

carbon footprints along the urban-rural-dimension. In Figure 2, OECD's consumption unit refers to the OECD's modified consumption unit scale recommended by Eurostat, where the first adult of the household receives the weight 1, other over 13-year-olds receive the weight 0.5, and younger children receive the weight 0.3 (Eurostat 2016). It is a common equivalence scale, but there are many others as well. As Figure 2 depicts, carbon footprints follow income regardless of the unit of analysis. In the thesis, regression models are used to control the impact of income and household size (type) on carbon footprints. Thus, the results would not be significantly different if carbon footprints per consumption unit or per household were studied. However, regression models have some weaknesses, as discussed in Section 2.3, which could potentially affect such comparison. The per capita perspective was chosen, since carbon footprint per capita is the most common unit of analysis in the carbon footprint literature (see Section 3.1). This makes the results of the thesis easy to compare with most of the previous studies in the field. However, in Paper III, OECD's consumption unit is used in addition to per capita assessment.

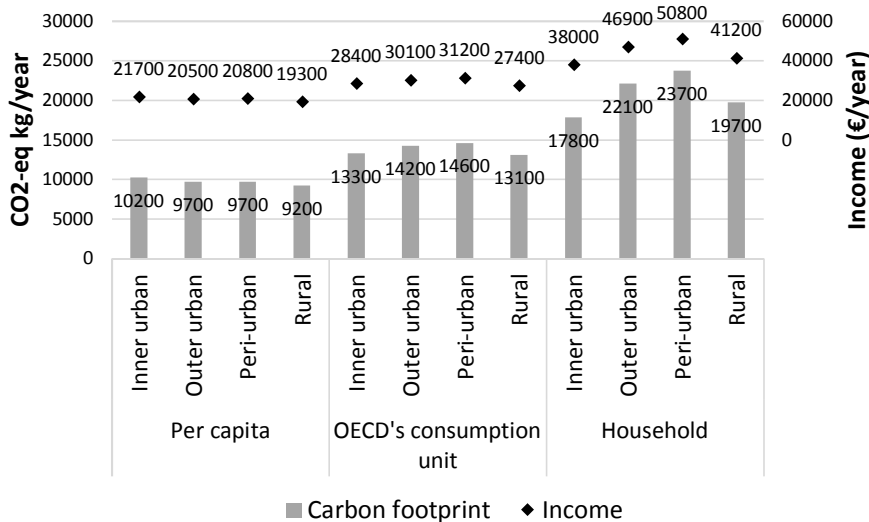


Figure 2. The impact of the unit of analysis on carbon footprints and income in various urban structures in Finland (Ottelin 2016)

2. Methodology of carbon footprinting

The thesis studies the carbon footprints of consumers in the built environment. This chapter clarifies what is meant by carbon footprint and how carbon footprints can be studied using regression models. The chapter begins by examining the main strengths and weaknesses of carbon footprinting compared to other GHG assessment methods. In other words, the chapter discusses the differences between the consumption-based and production-based method in GHG accounting for geographical areas, and the difference between EE IO analysis and process LCA. After this, the reader should have a clear understanding of what a carbon footprint is and why it is such an important concept. The last part of the chapter concentrates on how regression models can be used to study the effects of independent variables on carbon footprints.

2.1 Greenhouse gas accounting for human settlements

There are two basic methods for assessing the GHG emissions caused by a human settlement: the production-based method and the consumption-based method (Peters 2008; Dodman 2009; Chávez & Ramaswami 2013; Ramaswami & Chávez 2013). The production-based method can also be called geographical or territorial accounting. In essence, the methods convey different ideas about who or what is ultimately responsible for causing the emissions (Lenzen et al. 2007; Hoornweg et al. 2011). The production-based method allocates the emissions to the producer, for example a factory. All GHG sources and emitting activities taking place within the geographical boundaries of the studied human settlement are taken into account (ICLEI 2012, Greenhouse gas protocol 2014). These actions often include energy production, industry, ground transport and possibly agriculture and waste generation. In contrast, the consumption-based method allocates the emissions to the consumer. When a person buys a service or a product, all the emissions caused by the production process, raw material extraction, transportation, space heating, and so forth, are allocated to the buyer no matter where these particular processes have taken place. With the consumption-based method, the boundaries of the studied area determine only the population included in the accounting, not the location of the emissions. Naturally, the two methods lead to differing results. Wealthy cities and nations have usually higher consumption-based GHG emissions than production-based GHG emissions (Dodman 2009), due to their relatively low amounts of industrial ac-

tivity within the boundary and importing of GHG emissions via goods and services. However, this is not always the case (Chávez & Ramaswami 2013). Similarly, cities with heavy industry often have high production-based GHG emissions, but the emissions may be lower when consumption-based accounting is applied.

Figure 3 illustrates the differences between production- and consumption-based methods. Production-based method excludes emissions produced outside the city, but consumed within the city ('imported emissions'), whereas consumption-based method excludes emissions produced within the city, but consumed outside the city ('exported emissions'). While territorial accounting is a meaningful tool to manage GHG emissions within the city, it should not be used to compare the emissions per capita of different cities or other human settlements (Chávez & Ramaswami 2013). This would be misleading, since the territorial emissions caused by local industry, for example, are not directly associated with the residents of the area.

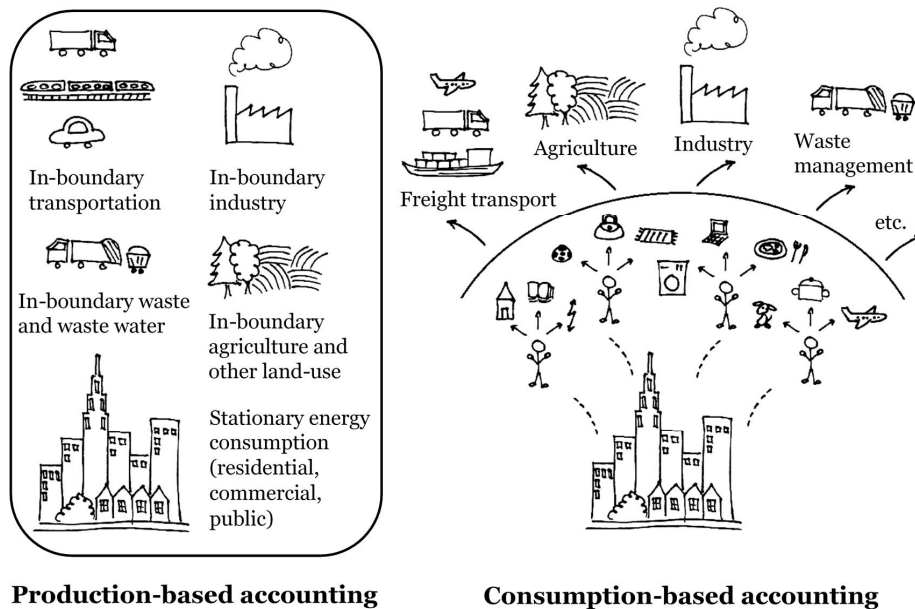


Figure 3. Comparison of production- and consumption-based GHG accounting for human settlements. Production-based method focuses on direct emissions. Consumption-based method has a life-cycle perspective – industrial processes, agriculture etc. are upstream processes needed to produce goods and services. (Ottelin 2016)

The production-based and consumption-based methods are often considered complementary. For instance, Wiedmann et al. (2015) have proposed a new concept called 'city carbon maps' to account for production-based and consumption-based emissions simultaneously. Basically the city carbon map is a matrix-like framework that provides information about the carbon flows of the city at a single glance for decision makers and other interested parties. The beauty of it lies in its inclusive, holistic view. Previously for example Lenzen et al. (2007), Dhakal (2010), Chávez and Ramaswami (2011), Ramaswami et al.

(2011), Erickson (2012) and Paloheimo and Salmi (2013) have presented similar ideas about the complementary nature of the production-based and consumption-based methods. Such a balanced view is also highlighted in the Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment Report (Edenhofer et al. 2014).

The thesis uses the consumption-based accounting, which is ideal for capturing the rebound effects. The focus of the thesis is not on the GHG accounting of areas, but rather in the possible consequences of various mitigation measures in the built environment. Moreover, the areas studied in the thesis are not based on municipal or other administrative boundaries, which makes the territorial accounting irrelevant in most cases. However, it should be noted that density policies and related transportation solutions may affect travel and consumption behaviour of other people, such as visitors and tourist, in addition to the residents of the city. This is not taken into account in the thesis. Nonetheless, while the producer-centric view is still the dominant one, consumption-based accounting provides new scientific insights, followed by practical policy implications that would not emerge from production-based accounting alone.

2.2 EE IO analysis and LCA – the concept of carbon footprint

Consumption-based GHG accounting is based on environmentally extended economic input-output (EE IO) analysis. However, EE IO analysis, which is essentially a life-cycle assessment method, can be applied from the producer's perspective as well. EE IO analysis was invented by Wassily Leontief. Leontief developed the input-output economics, for which he won the Nobel Prize in 1973. The input-output tables of an economy consist of monetary transaction matrices describing the various transactions between economic sectors. Each economic sector uses inputs to produce intermediate products (outputs that serve as inputs in other sectors) or final products and services (outputs). With environmental extension, pollution amounts or other environmental indicators are added to the matrices so that environmental burdens and how to eliminate them can be analysed (Leontief 1970). Input output analysis is a top-down method.

The input-output economics specify a relationship between total production and final demand:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{f}, \quad (1)$$

where \mathbf{x} is total output, \mathbf{f} is final demand and $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse (industry-by-industry, M€/M€), in which \mathbf{I} is the identity matrix (industry-by-industry) and \mathbf{A} is the intermediate use coefficient matrix (industry-by-industry). Each column of \mathbf{A} gives the intermediate industry outputs (M€) required to produce one unit of output (M€) of another. It is sometimes also called the technology matrix (Suh & Hupples 2005). With the environmental extension, emissions and resource consumption caused by the consumption of goods and services can be calculated as follows (Leontief 1970; Suh & Hupples 2005; Mattila 2011):

$$\mathbf{g} = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{M}\mathbf{f}, \quad (2)$$

where \mathbf{g} is the total emissions (resource consumption) caused by the final demand, \mathbf{B} is the emission (resource) intensity (emission and resource flow-by-industry, kg/€) and \mathbf{M} is the environmental multiplier matrix (emission and resource flow-by-industry, kg/€). For a more detailed description and derivation of the equations, see Leontief (1970), Suh & Huppes (2005) and Mattila (2013). In the case of carbon footprints, \mathbf{g} is the carbon footprint (scalar), \mathbf{M} is the GHG intensity of the consumption categories (vector) and \mathbf{f} is the expenditure on the various consumption categories (vector).

During the past few decades, environmental life-cycle assessment (LCA) has also been developed. The aim of LCA is to assess the environmental impact of a product, including its entire life cycle from raw material extraction to end-of-life treatment. Traditional LCA, also called process LCA, begins with specifying the goal and scope definition and continues on to inventory analysis, impact assessment and an interpretation of the results (ISO14040). It is a bottom-up method. While LCA has become quite popular, it has also been criticised for lacking a scientific basis, especially in the system boundary selection (Suh et al. 2004; Guinée et al. 2010). In practice, LCAs are often limited to the main processes causing environmental impacts. At some point, a researcher must decide which particular upstream processes to exclude. Often the lack of data, data quality and the large data requirements of traditional life cycle inventory affect these decisions. The exclusion of (upstream) processes causes the so-called truncation error. The truncation error may easily be understated by LCA practitioners, since all of the processes that are excluded seem insignificant compared to the main environmental burdens. However, environmental studies using input-output analysis have demonstrated that actually the excluded processes together can contribute significantly (even by >50%) to the total environmental impacts (Lenzen 2000; Suh et al. 2004; Nässén et al. 2007).

EE IO analysis is consistent with the idea behind LCA. When the environmental impacts of a product are assessed via EE IO analysis, all the upstream processes are included. Thus, it is called economic input-output LCA (EIO-LCA, or EE IO LCA) by some practitioners. It varies, however, whether it is classified as a type of LCA (e.g. Hendrickson et al. 1998) or as a separate type of analysis (e.g. Druckman 2011).

While EE IO analysis is a more comprehensive method than process LCA, it comes with the downside of roughness. The dividing of economic sectors causes an aggregation error: the emissions from a particular economic sector are allocated equally to each of the outputs (intermediate and final products). Thus, the model does not separate, for example, fine paper from cardboard if they are produced in the same sector. The model also includes an inherent assumption regarding the linearity of prices. This means that a €2 product is assumed to cause twice as much emissions as a €1 product produced in the same sector. The aggregation error and linearity assumption are sometimes also referred to as the

homogeneity assumption. The model assumes the homogeneity of prices, outputs and emissions at the sector level (Wiedmann 2009a). The differing weaknesses of process LCA and EE IO analysis are illustrated in Figure 4.

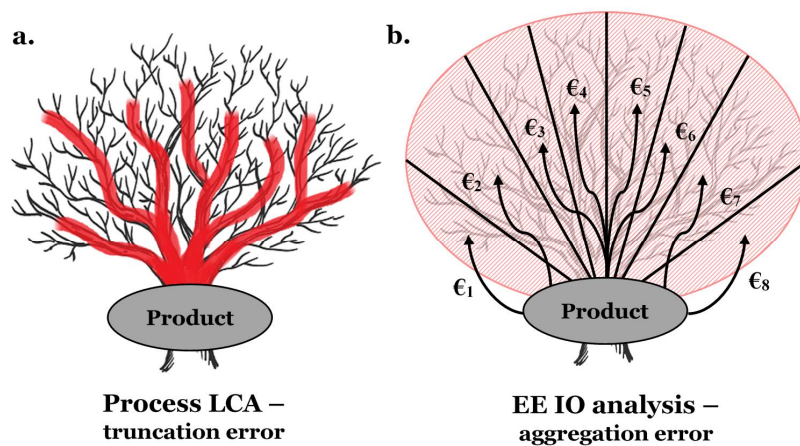


Figure 4. Process LCA (a.) is a bottom-up method focusing on the main processes (the thick red branches) that cause environmental impacts. It includes the truncation error (the thin black branches, the excluded upper-tier processes) caused by the system boundary selection. EE IO analysis (b.) is a comprehensive top-down method that also includes all the upper-tier processes causing environmental impacts, but at an aggregate level. (Ottelin 2016)

Another line of criticism with respect to the EE IO models has to do with the way they treat imports. In single-region models, it is assumed that the production technologies are the same for imported goods as they are for domestic goods (Suh & Huppes 2005). This is not usually true in reality, which leads to biases. To solve this problem, multi-region IO (MRIO) models have been developed (see, e.g. the review by Wiedmann 2009b). Although MRIO models suffer from uncertainties related to data availability and quality, they have a stronger theoretical basis than single-region models.

Since both process LCA and EE IO analysis have pros and cons, hybrid models have also been developed. Hybrid LCAs aim to increase the strengths and decrease the weaknesses of the EE IO and process LCA models (Suh et al. 2004). The hybrid models either integrate process LCA data into the EE IO model or else fill in gaps in the process LCA model with IO data. In theory, the EE IO analysis and hybrid LCA models can be used to assess any environmental impacts. However, it depends on the EE IO model, which environmental impact categories are included.

The EE IO analysis-based GHG assessments are often called ‘carbon footprints’ by practitioners. However, ‘carbon footprint’ is a broad concept that is used for other types of GHG assessments as well (Weidema et al. 2008). The other types of assessments are not discussed in the thesis. In the EE IO analysis literature the term ‘carbon footprint’ is well established and stands for all direct and indirect GHG emissions caused by an activity or during the life cycle of a product (Wiedmann 2009a). It is a captivating term, since it intuitively implies that it ‘encompasses all “traces” that an activity leaves behind’, as Wiedmann

put it. The thesis uses this particular EE IO analysis-based definition for carbon footprint.

In the thesis, the focus is on the carbon footprints of people: consumers, households, cities, nations, etc. The carbon footprint model used in the thesis is a hybrid LCA model based on EE IO analysis and the unit is CO₂-eq kg/year per capita. Prior carbon footprint studies are not consistent in whether they report CO₂ or CO₂ equivalents. Likewise, the EE IO analyses of energy requirements are included in the following literature review (Section 3.1), since they have similar implications as carbon footprint studies, at least in the case when energy production is mainly based on fossil fuels.

2.3 Regression models for carbon footprints

Regression analysis is used to establish a relationship between a dependent variable and an independent (explanatory) variable. In a multivariable regression model, there are more than one independent variables. If the aim is to study the effect of a particular variable, the other variables included in the model are called the control variables. It is either known or assumed that the control variables affect the dependent variable, and thus it is important to control their effect.

Carbon footprints, and consumption-based energy requirements, have a non-linear exponential relationship with income and expenditure (Lenzen et al. 2004; Lenzen et al. 2006; Weber & Matthews 2008; Shammin et al. 2010). Other models have been tested as well, but they have performed similarly or worse (Weber & Matthews 2008; Shammin et al. 2010). In its general form, the relationship is as follows:

$$CF = K \cdot E^\beta \cdot \varepsilon, \quad (3)$$

where CF is the carbon footprint, E is income or expenditure, K and β are constants, and ε is an error term. In the thesis, income refers to disposable income. Equation 3 can be rewritten as follows:

$$CF = e^{\beta_0} \cdot E^{\beta_E} \cdot e^{\beta_n D_n} \cdot e^u, \quad (4)$$

where $K = e^{\beta_0} = \text{constant}$ and $\varepsilon = e^{\beta_n D_n} \cdot e^u$. The term ' $e^{\beta_n D_n}$ ' is a dummy-variable term (explained below) and included in the model to control for and/or test the effect of various variables of interest. Equation 4 can be reformed to a convenient linear form by taking natural logarithms on both sides (Lenzen et al. 2004; Shammin et al. 2010):

$$\ln(CF) = \beta_0 + \beta_E \ln(E) + \beta_n D_n + u, \quad (5)$$

where β_0 is a constant, β_E is the regression coefficient for E, D_n is the n^{th} dummy or class variable, β_n is the regression coefficient for D_n , u is an error term and n

is $1 \dots n$. Dummy variables are variables that can only take a value of 0 or 1. They function as sort of on-off switches that make it possible to use a single model to describe multiple groups of people. While class variables behave similarly as dummy variables, they can have more than two exclusive classes, for example age groups. One of the classes is used as a reference group, and the regression coefficients give the relative effect of belonging to another subgroup compared to the reference group. Dummy and class variables can also be the particular variables whose effect is being tested.

The linear model (Equation 5) is convenient since the effect of dummy and class variables can be easily interpreted. The ratio between the compared groups is e^{β_n} . For example, if couples are compared to single people and the regression coefficient $\beta_1 = -0.12$, then the ratio ($CF_{\text{couples}}/CF_{\text{singles}}$) is $e^{\beta_1} = 0.89$, which means that the couples have, on average, a carbon footprint that is 11% lower per capita than that of single people. The negative coefficient stands for the decreasing effect, whereas the positive coefficient stands for the increasing effect.

One of the major issues that needs to be considered when applying regression analysis is the issue of multi-collinearity. It is problematic to include two or more explanatory variables that correlate with each other in the same model because it makes it impossible to interpret the results unambiguously. In the ideal case, all the independent variables would be exogenous, and thus, would not correlate with each other at all. In social sciences this is quite impossible, however, since so many socio-demographic variables correlate with income and with each other. Furthermore, omitting important variables is also misleading. For example, in their study on endogeneity Antonakis et al. (2010) suggest that researchers should opt to include too many rather than too few control variables in regression models. By contrast, Aguinis and Vandenberg (2014) highlight that the inclusion of each control variable must be strongly justified. Thus, viewpoints vary on whether it is more important to avoid omitting variables or to avoid including unnecessary variables. One way to circumvent the problem of multi-collinearity is to run a series of regression models with different variables and with a different number of variables. The effects of highly correlated variables can be tested using separate models (e.g. Lenzen et al. 2004; Lenzen et al. 2006).

When comparing regression models, the explanatory power of the regression model, R^2 , is a practical tool. In theory, the higher the value of R^2 , the greater the explanatory power and the better the fit between the data and the model. For example, when $R^2 = 0.8$, then the independent variables explain 80% of the variation in the dependent variable; only 20% of the variation is left unexplained by the model. However, the inclusion of new variables generally increases R^2 , but that does not necessarily mean a better model. Also, in the case of carbon footprints, expenditure results in a higher R^2 than income as an explanatory variable, but this is self-explanatory since carbon footprints are calculated by multiplying expenditures (see Section 2.2).

Income and expenditure carry different meanings as explanatory variables for carbon footprints. The total expenditure strongly determines a person's carbon

footprint and the effect of other variables is usually low in comparison. However, the model is highly deductive by nature. It explains the variation in the carbon footprints derived from expenditures by the variation in the total expenditures, while it does not explain the latter at all. In practice, the model describes the GHG intensity of consumption (Shammin et al. 2010). When income is used as the explanatory variable, the model can be interpreted as an attempt to explain expenditure and its derivative, the carbon footprint, by income. Both expenditure and carbon footprint can be considered as measures of consumption behaviour, which can be explained by income and other variables. However, the explanatory power of these models is often low because expenditure (consumption behaviour) depends on many things, not just on income and other selected variables.

In the case that expenditure or income is used as a control variable to study the effect of other variables on carbon footprints, as in the thesis, there are additional issues that need to be considered. Ultimately, it is a question of whether we think that the expenditure or the income of a person is constant. In most cases, it makes more sense to assume that income remains constant, since many mitigating measures may affect total expenditure, but not income. However, in some cases both assumptions are questionable and the regression models must be interpreted with caution.

3. Theoretical foundation

This chapter presents the theoretical foundation of the thesis. The thesis builds on two main theoretical threads: the theories and hypothesis regarding the determinants of carbon footprints and the theory on rebound effects. Both concepts are still evolving. While the studies on carbon footprints and rebound effects partly overlap with one another, mostly they can be divided into two separate fields of research. The first part of the chapter discusses how carbon footprints have been studied within the context of the built environment. The second part of the chapter deals with rebound effects.

3.1 Carbon footprints in the built environment

Carbon footprint literature refers in the thesis to the consumption-based studies on GHG emissions and energy requirements (see Sections 2.1 and 2.2). Several questions and hypotheses related to the built environment have been studied within this field. One of the most important questions regarding the built environment has to do with whether carbon footprints depend on urban structure or not. This has received a great deal of attention and a detailed review of such studies is provided below. Other broadly tested variables related to the built environment include dwelling type and car ownership. Prior studies have found that dwelling type does not have a significant impact on carbon footprints when income and household size are used as controls (Ala-Mantila et al. 2013; Heinonen et al. 2013b; Wiedenhofer et al. 2013). Car ownership and the number of vehicles correlate positively with carbon footprint (Ornetzeder 2008; Jones & Kammen 2014; Wiedenhofer et al. 2013; Heinonen et al. 2013b).

The connection between urban structure and carbon footprint has been the focus of several prior studies. The following literature review encompasses carbon footprint studies that include a measure for urban structure or the level of urbanity. The literature review is restricted to the 21st century, although several earlier studies include an urban-rural dimension as well (e.g. Herendeen & Tanaka 1976; Herendeen 1978; Lenzen 1998).

Table 1. Literature review of carbon footprint studies that include an urban structure variable

Author	Year	Measure for env. pressure	Measure for urban structure	Exp. or inc.*	Reg. co-eff. for the urb. var.**	Descriptive result or explanation for the regression coefficient
Lenzen et al.	2004	Energy req.	Sydney Statistical Subdivisions (SSD)	inc.	-0.003	Zero impact***
Lenzen et al.	2006	Energy req.	Population density (Australia, Brazil, Japan) or a dummy-variable (Denmark, India)	exp.	from -0.11 to 0.7, depends on the country	In most countries, increased urban density has a low decreasing impact on energy intensity
Ornetzeder et al.	2008	CO2	Car-free and a reference settlement in Vienna	-	-	The CO2-intensity of the car-free settlements is 20 % lower
Druckman and Jackson	2009	CO2	A classification based on socio-economic characteristics and residential location	-	-	"City living" households have 5 % higher income level than "Blue collar communities", but 4 % lower emissions
Baiocchi et al.	2010	CO2	Geodemographic consumer segmentation, UK	-	-	Affluence and household size seem to explain the emissions more strongly than the place of residence
Shammin et al.	2010	Energy req.	Urban-rural-dummy (1), population size of the area of residence (2), US	exp.	1.17 (1) 1.19 (2)	Rural areas and smaller towns have higher energy intensity
Heinonen and Junnila	2011	CO2-eq	Helsinki and Tampere core versus surrounding areas, municipality boundaries, Finland	-	-	The impact of urban density on carbon footprint is insignificant
Heinonen et al.	2011	CO2-eq	Helsinki downtown and surrounding suburban areas, Finland	-	-	The carbon footprints are higher in downtown due to higher consumption
Heinonen et al.	2013a	CO2-eq	Rural, semi-urban, urban and metropolitan cities/municipalities, Finland	-	-	Lifestyles are tied to the residential location and affect the carbon footprints through all consumption
Heinonen et al.	2013b	CO2-eq	Same as Heinonen et al. (2013a)	-	-	At equal income levels the carbon footprints are close to equal
Ala-Mantila et al.	2013	CO2-eq	Low-rise and apartment house living in the Helsinki metropolitan area	both	-0.03 (inc.) -0.03 (exp.)	Residents of apartments have 3 % lower carbon footprints
Wiedenhofer et al.	2013	Energy req.	Population density, Australia	inc.	-0.02 (direct energy req.)	The impact of urban density on energy requirements is low
Minx et al.	2013	CO2	Six types of human settlements, ranked according to the level of urbanization, UK	inc.	-	The impact of population density and the settlement type is very limited
Ala-Mantila et al.	2014	CO2-eq	Same as Heinonen et al. (2013a)	both	-0.13 (inc.) -0.19 (exp.)	Residents of Helsinki metropolitan area have 12 % lower carbon footprints than residents of rural areas, when income is controlled
Jones and Kammern	2014	CO2-eq	Zip codes: urban core, urban, urban fringe, suburban, rural fringe, rural, US	inc.	-	Suburbanization undermines GHG benefits of urban density

* Expenditure or income as independent variable (the dependent variable is carbon footprint or energy requirements).

** Regression coefficient for the urban structure variable of the study. See explanations in the next column.

*** In this table, 'impact' does not refer to a causal relationship between the independent and dependent variable, but simply the interpretation of the regression model.

Table 1 gives an overview of the studies and summarises their main points. The table gives the measure used for environmental pressure (carbon footprint or energy requirements) and the measure used for urban structure. The table also presents whether expenditure or income is used as an explanatory variable (for cases in which the study includes regression analysis) and provides the most relevant regression result relating to the impact of urban structure. The last column describes the meaning of the regression result and provides the main results from the studies that do not include regression models, again with respect to urban structure. The results presented in Table 1 concern carbon footprints or energy requirements *per capita*, with the exception of the studies by Druckman and Jackson (2009), Shammin et al. (2010) and Jones and Kammen (2014), all of which used *household* as the main unit of analysis.

As one can see, the studies using regression analysis suggest that increasing urban density either moderately reduces the size of carbon footprints (Lenzen et al. 2006; Shammin et al. 2010; Ala-Mantila et al. 2014; Jones & Kammen 2014) or has a very low impact on them or else no impact at all (Lenzen et al. 2004; Ala-Mantila et al. 2013; Wiedenhofer et al. 2013; Minx et al. 2013). The studies without regression analysis support the observation regarding lower GHG intensities in more urban settings (Ornetzeder et al. 2008; Druckman & Jackson 2009) and the insignificance of urban structure as an explanatory variable for the total carbon footprints (Baiocchi et al. 2010; Heinonen & Junnila 2011; Heinonen et al. 2011; Heinonen et al. 2013a, 2013b).

In general, the reviewed studies highlight that income (or expenditure) and household size are the main determinants of carbon footprint and that the impact of other variables is usually low in comparison. Several studies have also explored direct and indirect emissions separately (Lenzen et al. 2004; Shammin et al. 2010; Wiedenhofer 2013; Minx 2013; Ala-Mantila et al. 2014). These studies consistently reveal that the share of direct emissions is higher in rural and suburban areas than in dense urban cores. However, the lower direct emissions in urban cores are overridden by the higher indirect emissions. For example, Lenzen et al. 2004 and Wiedenhofer et al. 2013 conclude that policies focusing on direct energy requirements are probably misdirected in the case of city dwellers, whose energy requirements consist mostly of indirect energy consumption.

Several studies discuss the connection between the level of urbanity and income (Lenzen et al. 2004; Heinonen et al. 2013a, 2013b; Wiedenhofer 2013). People living in metropolitan areas generally have higher salaries and better job opportunities than in other areas due to agglomeration benefits (Glaeser & Gottlieb 2009). From this perspective, it is questionable to control for the effect of income when comparing the carbon footprints of rural dwellers with the carbon footprints of city dwellers, for example. On a larger scale, cities are important drivers of economic growth. In terms of city management, economic

benefits are often put before environmental benefits. Though urban density policies are expected to benefit both the economy and the environment, the tension between the two is not always well understood or else is ignored (Lenzen et al. 2004; Säynäjoki 2015).

A few studies discuss air travel. Lenzen et al. (2004) found higher energy requirements related to flying in the urban core than in the suburban areas of Sydney, whereas Heinonen et al. (2013a, 2013b) found that the emissions from air travel are higher in the metropolitan area than elsewhere in Finland. In a study by Ornetzeder et al. (2008), residents living in a car-free settlement in Vienna were responsible for higher emissions stemming from air travel than the reference group.

Many recent carbon footprint studies suffer from two main weaknesses. First, the urban structure indicators are quite crude, often based on municipal or other administrative boundaries. For example, Minx et al. (2013) acknowledge this limitation and suggest that the effect of urban structure on carbon footprints may be significant at higher levels of spatial granularity. Second, carbon footprint studies are usually purely descriptive since they are based on either cross-sectional or panel data, but not on longitudinal data, which would provide the strongest foundation for making causal claims.

Compared to the number of carbon footprint studies that include a measure for urban structure, there is an abundance of literature relating to the effect of urban structure on travel behaviour (see, e.g. Badoe & Miller 2000; Crane 2000; Cao et al. 2009; Ewing & Cervero 2010; Naess 2012) and direct (combustion-phase) GHG emissions, often from housing energy and ground transport together (Norman et al. 2006; Ewing & Rong 2008; Glaeser & Kahn 2010; Rickwood et al. 2008). These studies quite consistently demonstrate that increased urban density (combined with some other urban structure variables, such as connectivity and accessibility) reduces direct GHG emissions. It is important to understand that this finding does not contradict the findings presented in carbon footprint studies, which present similar results for ground transport and housing energy. The carbon footprint studies simply have different scope that includes the emissions caused by other consumption as well (see Section 2.1).

The focus of carbon footprint studies has generally been on creating models that explain (predict) the carbon footprints as accurately as possible. They have not concentrated on testing the effects of specific climate change mitigation measures. In point of fact, the effects of household-level mitigation actions, such as turning down one's thermostat or reducing one's daily driving, have been studied much more often using econometric rebound effect models. The next section discusses the concept of rebound effects and the varying terminology surrounding it in more detail.

3.2 Rebound effects

In the fields of industrial ecology, environmental economics and ecological economics, rebound effects refer to the unintended consequences of measures

taken to reduce environmental impacts. Usually they cancel out part of the expected environmental improvement. In the worst case, they reverse the outcome, such that the environmental impacts are more severe after the measure has been taken. In the literature, this is often called the backfire effect. In the best case, rebound effects can be unanticipated co-benefits or positive spill-over effects (Hertwich 2005). Rebound effect is usually defined as a percentage – for example, 20 % rebound means that 80 % of the expected pollution reduction is realized, and 20 % of the reduction is canceled out by the rebound effect.

Research on rebound effects began in the field of energy economics. Already in 1865, William Jevons presented evidence that the increased efficiency of coal-use actually led to increased consumption of coal instead of the expected decline (Jevons 1865). Hence, rebound effects are sometimes referred as ‘Jevons paradox’. Perhaps because of the history, rebound effects for energy efficiency measures have been most broadly studied. Rebound effects are often used to call into question the ability of technological energy efficiency solutions to mitigate climate change (Fronzel et al. 2012; Galvin 2014; Greening et al. 2000; Binswanger 2001). However, rebound effects are related to other environmental policies and actions as well.

Rebound effects are often categorised as direct, indirect and economy-wide effects. Direct rebound effects occur when an increase in environmental efficiency reduces the price of a particular service, which in turn leads to increasing demands for the service. For instance, an energy efficient car reduces fuel expenses, and may thus lead to increased driving. Indirect rebound effects occur when an environmental choice leads to monetary savings, which in turn leads to the increased consumption of other goods and services. For instance, the money saved from fuel expenses can be spent on other types of consumption aside driving just as well. The environmental impacts caused by the unintended increase of consumption after a particular environmental choice is called the rebound. Economy-wide rebound effects refer to the far-reaching consequences of environmental actions and policies in the economy and society (for classifications of economy-wide effects, see e.g. Hertwich 2005; Turner 2009; Font Vivanco & van der Voet 2014). Economy-wide rebound effects are beyond the scope of the thesis, however. Direct and indirect rebound effects can also be referred to as micro-economic or household-level rebound effects, whereas economy-wide effects can be referred to as macro-economic effects (e.g. Herring & Roy 2007).

It should be noted that different studies define ‘rebound effect’ differently (Binswanger 2001; Galvin 2014). Studies related to energy efficiency often use it as a term for the direct rebound effect alone. It can also be mathematically defined in several ways (Fronzel et al. 2012; Font Vivanco et al. 2014). Studies that use different methods to assess rebound effects should not be compared with one another because the differences in the results arise from differences in the methods and scope. For example, a common problem in many rebound studies is that the capital costs, such as the amount invested in energy efficient technology, are often excluded or treated in an offhanded manner. However,

many researchers have pointed out that the exclusion of capital costs is questionable (Henly et al. 1988; Greening et al. 2000; Turner 2012) and that the inclusion of capital costs in the analysis results in lower rebound effects (Mizobuchi 2008; Nässén and Holmberg 2009; see also theoretical framework presented by Hertwich 2005). More recently, rebound studies by Chitnis et al. (2013, 2014) and Font Vivanco et al. (2014, 2015) have highlighted the need to include the capital costs in the analyses. Their results suggest that the capital costs related to environmental alternatives can even lead to negative rebound effects, that is to say, they result in additional environmental benefits due to decreased levels of consumption. Similarly, environmental alternatives that save a great deal of money often lead to high rebound effects, sometimes even to a backfire effect.

Table 2 presents some previous econometric rebound studies that include capital costs and the embodied emissions of the investment. Embodied emissions mean the life cycle emissions of the investment, for example the emissions caused by the production of insulation materials in the case of increased insulation. The studies also include both direct and indirect rebound effect.

Table 2. Econometric rebound studies that include capital costs

Author	Year	Measure for env. pressure	Studied mitigation measures	Impact of capital costs
Mizobuchi	2008	CO2	Energy efficiency measures related to electricity, gas, heating oil and car transportation	Inclusion of additional capital costs reduced the overall rebound effect from 115 % to 27 %.
Nässén & Holmberg	2009	Energy	Energy efficiency measures related to heating, home appliances and driving	Measures that cause capital costs result in lower rebound effects.
Chitnis et al.	2013	GHG	Seven GHG mitigation measures related to housing energy (insulation, lighting etc.)	Inclusion of capital costs reduced the rebound effects and led to a negative rebound in the case of 'solar thermal'.
Chitnis et al.	2014	GHG	Six GHG mitigation measures related to housing energy (insulation, lighting etc.)	Inclusion of capital costs generally reduced the rebound effects.
Font Vivanco et al.	2014	GHG and several others	Electric, hybrid and hydrogen fuel cell cars	Negative GHG rebound for full-battery electric car and hydrogen fuel cell car, low (<5 %) GHG rebound for hybrid car
Font Vivanco et al.	2015	GHG and several others	Transport eco-innovations (bicycle sharing system, car sharing, catalytic converter etc.)	Only innovations in which the change in transport costs is negligible or positive (bound income) decrease environmental pressure

Carbon footprint studies, such as the thesis, inherently include capital costs, since they study real, not modelled, expenditure and disposable income. However, it depends on the carbon footprint model, whether it includes the embodied emissions or not. The thesis includes the embodied emissions of construction and vehicle production, but only as simple approximates (see Papers II and IV). Moreover, the emissions of construction are taken into account in a con-

ventional way, by dividing the emissions by the expected life span of the building. However, this may be problematic because of the carbon spike of construction (Dutil et al. 2011; Passer et al. 2012; Säynäjoki 2014, see also Paper II). The emissions of the residents of new buildings are actually a lot higher than the emissions of the residents of old buildings possibly for decades, when the timing of the emissions is taken into account (Säynäjoki 2014). On the other hand, also the instalments of the housing loan can affect consumption for decades, leading to additional emission reductions annually.

Some rebound studies have also discussed the importance of including savings, since they are a source of funds for capital investment that cause GHG emissions (Druckman et al. 2011; Chitnis et al. 2013; Chitnis et al. 2014). Similarly as in the case of capital costs, the carbon footprint comparisons of the thesis inherently include monetary savings, i.e. the differences in saving ratios between the studied groups. However, they do not include the GHG emissions related to savings.

3.3 Connection between carbon footprints and rebound effects

There is a clear connection between studies on household-level GHG rebound effects and studies on the carbon footprints of consumers. Both types of studies use household budget surveys and the GHG intensities provided by the EE IO models. Rebound studies use econometric models based on the income elasticities of expenditure to estimate the rebound effects (Nässén & Holmberg 2009; Druckman et al. 2011; Chitnis et al. 2013; Murray 2013; Thomas & Azevedo 2013a, 2013b; Chitnis et al. 2014). Because of the theoretical nature of such studies, they include various assumptions and high levels of uncertainty. Carbon footprint studies, on the other hand, are based on real, not modelled, consumer expenditures and disposable income. They often discuss rebound effects, which provide a plausible explanation for some observations. However, their focus has not been on the rebound effects themselves; rather, they have attempted to explain carbon footprints using various variables. Thus, the existing literature still lacks a carbon footprint-based definition for household-level GHG rebound effects. Such a definition is presented in the discussion chapter (Section 5.1) as the theoretical implication of the thesis.

3.4 Attributional and consequential LCA

The carbon footprints and rebound effects also relate to another broader context in the field of life-cycle assessment. There is an ongoing debate about attributional and consequential LCA (Weidema et al. 1999; Ekvall et al. 2005; Earles & Halog 2011; Zamagni et al. 2012). Attributional LCA describes the situation as it is, whereas consequential LCA models the consequences of a particular decision. Carbon footprints are assessed using attributional LCA, whereas the rebound effect studies using econometric models represent consequential LCA (Earles & Halog 2011). The purpose of consequential LCA is to describe changes instead of static conditions. However, as noted earlier with respect to rebound

studies, the modelling of consequences includes various assumptions and high levels of uncertainty. For instance, Zamagni et al. (2012) point out that the market mechanisms that are taken into account in consequential LCAs is not the result of a systematic decision. Since both attributional and consequential LCAs include weaknesses, neither can be declared more 'correct' than the other (Ekvall et al. 2005; Zamagni et al. 2012).

The thesis studies attributional carbon footprints. One of the main issues related to this has to do with the use of average (attributional) emissions for electricity and heat production in the hybrid LCA model. With a consequential LCA model, marginal emissions could be used if the aim was to describe the GHG impacts caused by changes in the consumption of electricity or heating energy. However, such an assessment is beyond the scope of the thesis.

4. Empirical contribution

The thesis addresses the following research question: *How does the allocation of expenditures and the resulting GHG emissions differ between a group that has not adopted (been affected by) the studied mitigation measure and another group that has adopted the measure?* Mitigation measures refer both to measures that consumers have adopted and to policy measures that have affected consumers. The mitigation measures are represented by rather crude dummy and class variables. The research question is answered below based on the results presented in Papers I–IV. Each of the studied mitigation measures is examined separately. The implications of the results are elaborated in the discussion chapter (Chapter 5).

Car ownership and driving

Many of the efforts to mitigate climate change in the built environment target car ownership and the emissions caused by cars, for example density policies, car-pooling, electric vehicles, substituting driving with cycling, and so forth. This issue inspired Papers I and IV of the thesis, which explore the tail-pipe emissions resulting from personal travel (Paper I) and carbon footprints (Paper IV) depending on car ownership, the amount of driving and urban structure. Tail-pipe emissions mean the emissions caused by the combustion of motor fuel. Paper IV focuses on middle-income working people in Finland. It demonstrates that the amount of driving correlates strongly and positively with carbon footprint, but surprisingly, car-free people do not have the lowest carbon footprints. Instead, people who own a car, but who drive very little, have on average a carbon footprint that is 11% lower than the car-free subgroup. The car-free people have higher emissions especially from holiday trips, public transport and services. Paper I presents similar findings, but includes only personal travel. When middle-income car-owners and car-free people living in the Helsinki metropolitan area are compared, car-owners have high emissions from driving and negligible emissions from flying, while the opposite is true for car-free people (Paper I). The total emissions resulting from personal travel are almost equal in both subgroups. Paper I increases the reliability of the results presented in Paper IV since it uses a different dataset. The connection between car ownership and flying habits is found both in travel behaviour data, based on vehicle kilometres travelled (VKT), and in household budget data, based on monetary consumption.

In Paper IV, the rebound effects were estimated using a simple econometric model. It was assumed that the released funds would be spent entirely on items in the selected consumption categories. Savings were not considered, because there was little difference in the real saving ratio between the compared car-free and car-owning groups. The expenditure/income ratio was actually a little higher for car-free singles and couples than for car-owning singles and couples, but the opposite was true for families with children. For cases in which the released funds were spent on average consumption items (without personal vehicles and housing factored in), the results suggest a low (~20%) GHG rebound effect for reduced driving and a high (~70%) GHG rebound effect for giving up car ownership altogether. The average carbon footprints of the studied groups illustrate these average rebound results quite well. The modelled rebound for giving up car ownership vary in the study from 30% to 120%, depending on the alternative types of consumption.

Energy efficient housing in different urban structures

Paper II presents the carbon footprints of people living in new energy efficient houses versus older homes in three different urban zones in Finland. All urban areas in Finland are included. The main finding is that the energy efficient housing has reduced carbon footprints in the outer urban areas, but not in the inner urban areas. The reduction in the size of carbon footprints in the outer urban areas is mainly due to the lower emissions from housing energy, but there are some additional reductions in other types of consumption. Furthermore, urban structure is not a statistically significant explanatory variable for carbon footprints in Paper II, when income and household type (young, seniors, adult couples, etc.) are controlled for. Thus, it seems that carbon footprints are currently similar in size in different urban areas for households with otherwise similar characteristics, but the direction of the emissions is declining in the outer urban areas, whereas no such trend is found in the inner urban areas with respect to energy efficiency. The absolute carbon footprints are highest in new buildings in the inner urban areas due to high levels of affluence and a small average household size. Although the residents of new buildings have slightly lower emissions from housing energy than do the residents of older buildings in the inner urban areas, the high rate of other types of consumption more than counteracts this GHG reduction. In light of these results, the new construction in city centres does not seem to meet the expectations of the environmental claims, despite the lower amount of driving compared to the suburban areas.

Sharing of resources

As the literature review of carbon footprint studies in Section 3.1 reveals, the main determinants of carbon footprint are income and household size. Household size reduces carbon footprint per capita because of the household-level economies-of-scale effect (e.g. Wier et al. 2001; Lenzen et al. 2006). Larger households share GHG-intensive resources, such as shelter and energy, which

reduces the emissions on a per capita basis. The implications of this intra-household sharing for collaborative consumption or a sharing economy has not been discussed much in the existing literature. Paper III makes this contribution and, furthermore, demonstrates how intra-household sharing is connected to urban structure. The results demonstrate that while all of the consumption categories are to some extent shared within households, the home-related consumption categories, including electricity and heating, are most clearly shared. Surprisingly, personal vehicles are not very clearly shared; instead, the emissions increase first with an increase in the household size, and then they begin to decrease slowly since the third added household member. The regression results suggest that intra-household sharing and the resulting GHG benefits alleviate the harmful effects of urban sprawl. Specifically, an additional adult in a household reduces the carbon footprint per capita most strongly in the peri-urban areas.

Urban structure

Several previous carbon footprint studies have explored the connection between carbon footprints and urban structure (see Section 3.1). The contribution of the thesis with respect to these studies is that it explains the similarity between total carbon footprints in different urban structures especially via the rebound effects for reduced car ownership and driving, but also by means of other issues covered in the thesis. Also, the urban-rural classification used here is more detailed than in previous carbon footprint studies, and it is based on such variables as accessibility and distance from the city centre instead of municipal or other administrative boundaries. The classification highlights well a decrease in GHG emissions resulting from driving with increasing levels of urban density, but, at the same time, it shows that the total carbon footprints are strikingly equal at equal income levels regardless of the urban structure. The residents of the inner urban areas have higher emissions especially from holiday travel, public transit, services, housing maintenance and less pronouncedly also from tangibles.

Urban density policies generally aim to reduce VKT and the direct emissions caused by driving, and in this they are quite effective (see, e.g. Badoe & Miller 2000; Crane 2000; Cao et al. 2009; Ewing & Cervero 2010; Naess 2012). Increasing levels of urban density reduce both car ownership and driving. Often, the decline in car ownership is seen in an equally positive light as the decline in VKT. However, this may be misleading because of the high rebound effect for reduced car ownership, as demonstrated in Papers I and IV. The surprisingly high carbon footprints of middle-income working car-free people can partly explain why the carbon footprints in the inner urban areas are higher than expected. The question of which comes first, the inner urban location, the choice to be car-free or a more cosmopolitan lifestyle, has been left unanswered. High urban density levels, car-free living and the metropolitan area itself are all associated with high amounts of flying.

A further explanation for the similarity in the size of carbon footprints is provided in Paper III. Intra-household sharing compensates for the higher emissions levels from personal vehicles in the suburban areas. An additional adult provides a stronger economies-of-scale effect and related GHG benefits in the suburban areas than in the inner urban areas and Helsinki. The results suggest that the residential location affects the carbon footprints of families with children to a relatively minor degree. In Finland, however, the living space per capita does not vary between the inner urban and suburban areas as much as in some other countries (see, e.g. Paper II).

The new energy efficient housing has not yet had a strong impact on the total carbon footprints of any area since the share of these houses is still relatively low (~10%). Nonetheless, the increasing use of heat pumps also in older buildings in the suburban areas may have additional impacts. Together, these changes may partly explain why the suburban areas perform relatively well, contrary to expectations.

Overall, the regression results presented in the thesis support quite well the findings presented in the previous literature on the connection between carbon footprints and urban structure. According to the results of Paper II, the urban structure is not a significant explanatory variable for the carbon footprints when controlling for income and the household type ($R^2 = 0.49$). Paper III found that there is little difference between the inner, outer and peri-urban areas, but that the GHG intensity of consumption is lowest in Helsinki (the capital), which is separated out from the other areas in the study. The residents in the other suburban and inner urban areas (elsewhere in Finland) have carbon footprints that are 5–9% higher than the residents in Helsinki when controlling for expenditure ($R^2 = 0.85$) (see Section 2.3 for an explanation of the difference between income and expenditure as explanatory variables). In Paper IV, which only focused on the middle-income working people, the results demonstrated that the carbon footprints are 6% higher in the outer urban areas and 9% higher in the peri-urban areas than in the inner urban areas when controlling for income and household size. There was no statistically significant difference between the rural and the inner urban areas, however. Also, the R^2 proved to be quite low (0.23), which means that most of the variation (77%) in the carbon footprints could not be explained by the model. The low R^2 is due to the fact that the paper only focused on middle-class households. Income is the main driver of carbon footprint, and if it is left out or restricted in the regression model, then the explanatory power of the model drops noticeably. As a conclusion, the thesis as well as prior carbon footprint studies suggest that increased urban density either reduces carbon footprints to a small degree or else has no significant impact at all when controlling for income and household size.

5. Discussion

The thesis is based on comparisons of carbon footprints between groups of people who have not adopted (or been affected by) the studied mitigation measures and other groups of people who have adopted them. Intuitively, we would expect the carbon footprints to be much lower among the people who have adopted the mitigation measures. However, this is not always the case due to variations in the allocation of expenditures and the resulting GHG emissions. The key concept of the thesis is rebound effect, which refers to the unanticipated consequences of mitigation measures due to shifts in consumption patterns. Although the thesis examines static carbon footprints, it discusses the implications and provides working hypotheses regarding the possible dynamic shifts in consumption that could occur after the mitigation measures have been adopted.

This chapter is structured as follows. Section 5.1 presents the theoretical and methodological implications of the thesis, and binds the concepts of carbon footprint and rebound effect together. The chapter provides the reasoning behind the rebound implications discussed in the thesis. Section 5.2 considers the implications of rebound effects for the studied mitigation measures and the resulting policy implications. Broad policy implications and a summary of the policy implications of the thesis are included in the end of Section 5.2. Section 5.3 evaluates the research and Section 5.4 provides recommendations for future research.

5.1 Theoretical and methodological implications

Generally, rebound effect is defined as percentage as follows (Druckman et al. 2011; Chitnis et al. 2013):

$$RE = \frac{\Delta H_e - \Delta H_a}{\Delta H_e} \cdot 100\%, \quad (6)$$

where ΔH_e is the expected GHG savings and ΔH_a the actual GHG savings. The expected savings refer to the direct GHG emission savings that are expected to result from the mitigation measure when rebound effect is not taken into account. The actual savings refer to the actual GHG savings that are achieved after the mitigation measure has been adopted and rebound effect has taken place.

Font Vivanco et al. (2014) reformed this definition as follows:

$$RE = \frac{\Delta H_e - \Delta H_a}{|\Delta H_e|} \cdot 100\% \quad (7)$$

The benefit from the addition is that ΔH_e can be negative (< 0), i.e. the emissions may be expected to rise. This can be the case, if the aim is to reduce some other environmental burden instead of GHG emissions, for example (Font Vivanco et al. 2014).

As mentioned in Section 3.3, the existing literature lacks a carbon footprint - based definition for household-level GHG rebound effects. Such a definition is presented below in Figure 5. The definition is derived from the existing rebound effect literature, and it simply links the rebound effects concretely with carbon footprints. Note that the GHG savings ΔH increase, when the GHG emissions (Y-axis) decrease.

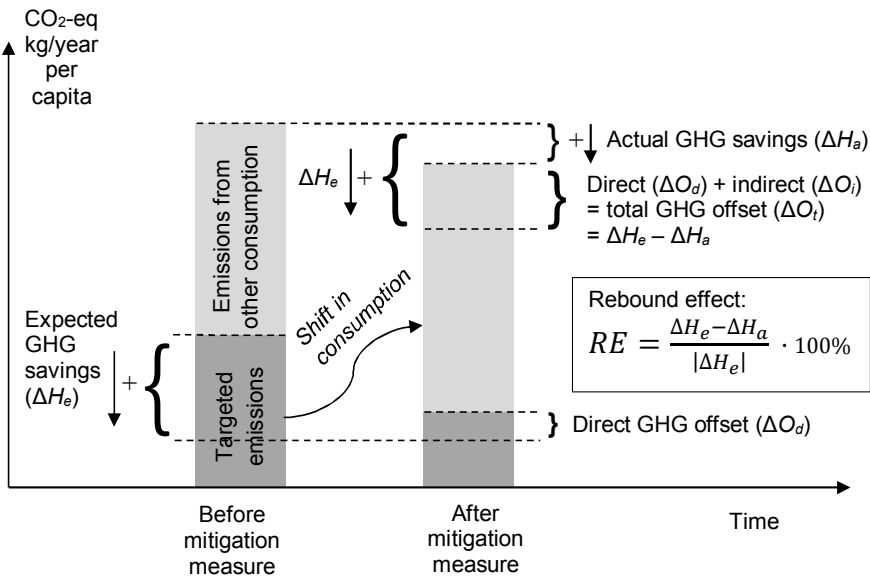


Figure 5. Household-level rebound effect for a climate change mitigation measure (Ottelin 2016)

With Figure 5, direct rebound effect is defined as:

$$RE_d = \frac{\Delta O_d}{|\Delta H_e|} \cdot 100\%, \quad (8)$$

indirect rebound effect as:

$$RE_i = \frac{\Delta O_i}{|\Delta H_e|} \cdot 100\% = \frac{\Delta O_t - \Delta O_d}{|\Delta H_e|} \cdot 100\% \quad (9)$$

and total rebound effect as:

$$RE_t = \frac{\Delta O_t}{|\Delta H_e|} \cdot 100\% = \frac{\Delta H_e - \Delta H_a}{|\Delta H_e|} \cdot 100\% \quad (10)$$

To keep the theoretical framework simple, the time span is not defined here, but it should be noted that the rebound effect may vary depending on time (e.g. Font Vivanco & van der Voet 2014). With a long enough time span, even the economy-wide rebound effects could realize.

The main benefit of the new graphical framework presented in Figure 5, is that it can be applied to study both direct and indirect rebound effects for mitigation measures with empirical carbon footprints instead of econometric modelling. However, it would require a longitudinal research design. In practice, often only cross-sectional data are available. Thus, Figure 6 presents a practical approach to estimating the approximate rebound effects with cross-sectional carbon footprints. The implications of the rebound effects discussed in the thesis are based on this approach.

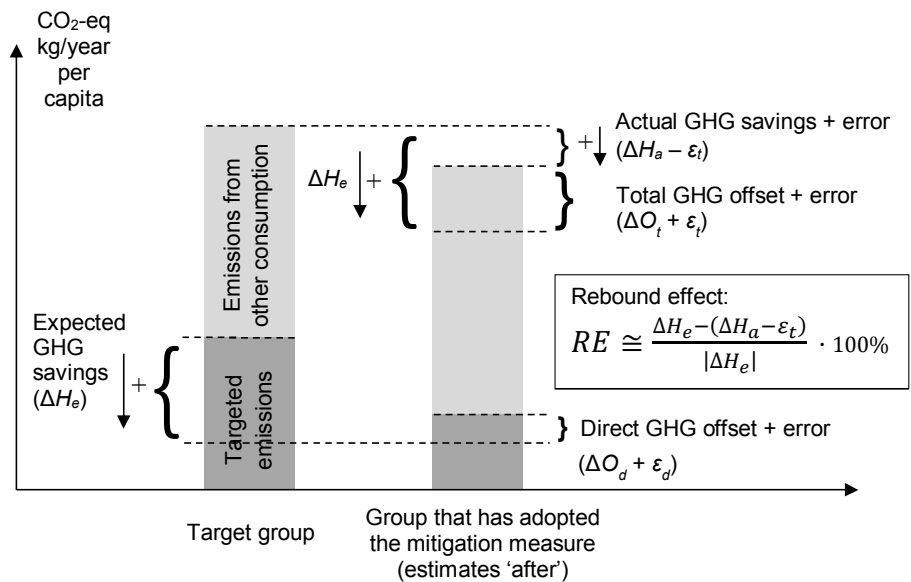


Figure 6. Practical approach to estimating the rebound effect with cross-sectional data. The errors are mainly due to self-selection bias (see below) and they can be either positive or negative. The error for ΔH_a is the additive inverse of the error for ΔO_t (Ottelin 2016).

Figure 6 describes a static situation without the time dimension and dynamic shift in consumption patterns shown in Figure 5. To put it simply, people are divided into a target group, which has not adopted (or been affected by) the studied mitigation measure, and an estimation group, which has adopted the mitigation measure. The target group represents the 'before' in Figure 5, whereas the estimation group estimates the 'after'. The problem, however, is that the estimation group is actually a separate group of people, and there are other differences between the studied groups aside the mitigation measure – and these other differences may affect the carbon footprints.

This dilemma is called the self-selection bias in statistics. It arises from having selected the studied groups instead of using random sampling, control groups and a longitudinal research design (for more on residential self-selection in

travel behaviour studies, see Cao et al. 2009; Ewing & Cervero 2010). The self-selection bias can be reduced by controlling for some of the possible differences between the studied groups via regression models. However, the estimation is likely to be more correct if the studied groups are similar to start with. For example, if there are strong differences in the household size or the income levels between the studied groups, the collinearity problems related to regression models will increase since the variable of interest (the mitigation measure) correlates strongly with the household size or income (see Section 2.3). Also, other important variables may have been omitted that affect carbon footprints. Because of such problems related to self-selection, the presented approach cannot be used to accurately predict the rebound effects. However, it can be used to assess the qualities of the studied rebounds: whether they are high or low, positive or negative.

Paper IV provides an interesting comparison between the practical approach to estimating the rebound effects with carbon footprints (presented above) and a more traditional rebound effect study. In the paper, the rebounds are calculated both with a simple theoretical model similar to the existing econometric models found in the rebound literature and with the approach presented above. Interestingly, the two approaches yield similar, but not exactly the same, results.

5.2 Implications on rebound effects and policy implications

Car ownership and driving

The results presented in Paper IV suggest that the average rebound effect for reduced driving is low (~20%), whereas the average rebound effect for giving up car ownership altogether is high (~70%). The first result is well in line with previous studies on rebound effects (Sorrell 2007; Druckman et al. 2011; Murray 2013; Chitnis et al. 2014). The second result has not been studied before with the focus being on middle-income working people. This purposeful restriction brings out the rebound effects more clearly, since the income level and mobility needs of the compared groups are similar.

The high rebound effect for reduced car ownership supports the existence of a negative rebound effect related to capital costs (Chitnis et al. 2013, Font Vivanco et al. 2014, see also Section 3.2). Here, the amount invested in a car and the additional costs related to insurances, taxes, and so forth, are withdrawn from other types of consumption. Font Vivanco et al. (2014) presented similar results in their study on the rebound effects for electric cars.

At the policy level, the results imply that policies aimed at reduced driving and (middle- and high-priced) low-carbon vehicles could be more effective than policies aimed at car-free living. Low-carbon vehicles require an investment, which reduces other types of consumption and the related emissions. In contrast, adopting a car-free lifestyle means that funds can be used for other types of consumption, which may lead to a high rebound effect. However, both Papers I and IV highlight that one of the main reasons for the relatively high emissions in the car-free subgroup is the high amount of flying. Thus, for cases in which flying is

not a reasonable option, relinquishing car ownership might not have such a high rebound effect. Similarly, at the individual level, a car-free person can of course choose not to fly, which would reduce the rebound effect.

It should be noted that the focus on middle income class sets some limitations on the generalisability of the results. Paper I establishes that the trade-off between car ownership and flying is not significant in the other income groups. It is likely that people in the lower income class spend the funds released from car ownership on necessity items instead of luxuries, such as air travel. Thus, creating residential areas that enable car-free living for lower income people may be beneficial from a GHG perspective. On the other hand, necessities such as heating energy and food, generally have relatively high GHG intensity, which would again increase the rebound effect. Paper I only includes transport related emissions. The higher income class includes very few car-free households.

Energy efficient housing in different urban structures

Paper II provides interesting insights into the possible rebound effects for energy efficient housing. In the outer urban areas, the carbon footprints of residents living in the new houses are lower mainly because of the lower emissions from housing energy, but there are additional GHG reductions in other consumption categories as well. This is surprising since prior studies on the rebound effects suggest that the increased energy efficiency of heating should have positive direct and indirect rebound effects (Greening et al. 2000; Hens et al. 2010; Thomas & Azevedo 2013a, 2013b). The opposite outcome supports the existence of negative rebound effects related to capital costs (see above or Section 3.2). In this case, the housing loan seems to constrain other types of consumption. However, the same situation is not found in the inner urban areas, not even when just the homeowners are studied. It is difficult to say why this is the case. One possible reason is that the most affluent people live in the inner urban areas and their consumption patterns are not limited by monetary constraints. Nonetheless, the results imply that the size of the household-level rebound effects for energy efficiency measures can vary in different urban structures.

Sharing of resources

The results presented in Paper III suggest that the rebound effects are low when GHG-intensive resources are shared. Although the focus of the paper is on intra-household sharing, this could be applied to inter-household sharing as well. For example, shared flats could reduce both heating energy and home electricity consumption per person. Collaborative consumption seems an attractive mitigation possibility especially in the inner urban areas, where small households tend to be concentrated. However, the results presented in Paper III suggest that there are additional reduction possibilities related to the sharing of resources in the suburban areas, too.

Urban structure

Changing urban structure is a heavy and complex measure to affect the GHG emissions. It does not only affect the daily travel behaviour of people, but also their long-distance travel (Papers I and IV; Brand & Preston 2010; Holden & Norland 2005; Holz-Rau et al. 2014), consumption behaviour, time-use and lifestyles (e.g. Baiocchi 2010; Heinonen et al. 2013a, 2013b), and the feasibility of technological mitigation measures, such as low-carbon construction materials and certain energy solutions (Paper II; Sathre & Gustavsson 2009; Graziano & Gillingham 2014). If the aim is to reduce the GHG emissions from driving, then all these other effects can be considered rebound effects. They may include co-benefits, such as green consumerism, related to the urban lifestyle. However, carbon footprint studies, including the thesis, suggest that the overall effect of urban structure on carbon footprints is small when household size and income are kept constant. Also, when national densification and centralisation policies are the point of focus, it is questionable whether or not to exclude the effects of changes in household income. Large cities and metropolitan areas have the highest salaries and best job opportunities. Rural areas are associated with relatively low carbon footprints simply because of the lower income level of people in such places compared to other areas. The migration from rural areas to cities is likely to be connected to increasing income levels, which in turn leads to increasing emissions. Thus, while encouraging it may be justified with economic and social aspects, it is unlikely to lead to GHG reductions.

There is still a lack of studies on carbon footprints that adequately explore the effect of urban structure within cities. In these cases, controlling for the effect of income is essential because whereas the residential location does not affect income within the city, income does affect the choice of residential location. The paucity of such studies is probably due to a lack of high-quality data. Nonetheless, current carbon footprint studies can be criticised for using crude measures for urban structure. Furthermore, they are usually purely descriptive and thus unable to make strong causal claims.

In conclusion, the effect of urban structure and related policy instruments on total GHG emissions is still an open question. The current emphasis on driving-related emissions seems misleading, however. Furthermore, determining the type of urban structure that should we built is a highly value-loaded question. People have very diverse preferences, and the preferences change during a person's lifetime (Walker & Li 2007; Strandell 2011; Kyttä et al. 2013; Lawton et al. 2013). Lenzen et al. (2004) argue that a prerequisite for promoting environmental-friendly behaviour is allowing participation. When consumers can choose their own areas, reasons for and means of protecting the environment, they may be more committed to doing so (Lenzen et al. 2004), and even more inventive. A diverse urban structure with area-specific, and in the best case, participatory mitigation measures could be a much more effective policy for addressing climate change in the built environment than merely increasing urban density as a general rule. The results of the thesis suggest that it would be quite possible to

create a low-carbon path for dense inner urban cores and low-rise suburban areas alike, without favouring either type of area.

Broad policy implications

Carbon pricing is often discussed as one of the policy implications for carbon footprint studies (Wiedmann et al. 2007; Weber & Matthews 2008) and rebound effect studies (Mizobuchi 2008, Druckman 2011, Chitnis et al. 2014), and sometimes even in transport studies (Brand & Preston 2010, Brand & Boardman 2008).

Policy instruments related to carbon pricing include carbon taxes, carbon caps and carbon trading systems. The aim of carbon pricing policies is to enhance low-carbon technologies, products and services, and to promote the technical upgrade or exit of the most emission-intensive production methods (Kosoy et al. 2015). According to a recent report by the World Bank (Kosoy et al. 2015), currently about 12% of global GHG emissions are covered by international, national and local carbon pricing instruments – and the amount is continuously increasing. However, there is a high degree of variation in the prices (from US\$1 to US\$130 per tCO₂-eq) and other specifications of the policy instruments. The report highlights that international cooperation is needed to avoid concerns about the impact of carbon pricing on competitiveness. On the other hand, some firms see carbon pricing as a competitive edge. An increasing number of firms are using internal carbon pricing as a strategic tool to identify low-carbon opportunities and manage the risks (Kosoy et al. 2015) related to changing legislation and increasing levels of environmental consciousness among customers, for example. Also, the report points out that international carbon leakage has not materialised on a significant scale, and that the risks can be managed through careful policy design.

It is important to consider the equity and fairness of the carbon pricing policies as well. For instance, Lenzen et al. (2004) and Wiedenhofer et al. (2013) discuss the problematics of policies that target direct emissions, that is to say, the emissions from motor fuels and energy production. Low-income households spend a larger share of their disposable income on these consumption categories than do high-income households. Thus, carbon pricing policies would most strongly affect households in the weakest position. However, such problems can be overcome by additional current transfers. For instance, the revenue from the carbon tax is in some countries returned to the citizens through lower public service costs (Kosoy et al. 2015).

Another broad policy suggestion that is gaining momentum is degrowth. Since income and economic growth are the main drivers of GHG emissions, and many other environmental impacts, it has been suggested that degrowth and reduced income levels, by reduced work time for example, could effectively reduce the environmental pressure caused by human activities (Schneider et al. 2010; Knight et al. 2013, Nässén & Larsson 2015). Some degrowth advocates even consider it as a necessity to achieve ecological sustainability (Schneider et al. 2010). At the individual level downshifting and slow-living trends represent similar

movement. However, there may be a contradiction between welfare state and degrowth (Bailey 2015). The social sustainability issues are a concern (Kallis 2011). This debate is however outside the scope of the thesis.

As a conclusion, the main policy implications of the thesis are presented in Table 3.

Table 3. Main policy implications of the thesis

General policy implications	
Carbon pricing	Carbon pricing policies based on international cooperation would offer an upper-level solution to climate change mitigation.
Energy efficiency policies	Rebound effect studies that question the effectiveness of energy efficiency measures often do not include the capital costs. The results of the thesis suggest that the negative rebound related to energy efficiency investments cause significant additional GHG reductions.
Renewable energy production	Renewable energy production affects the GHG emissions throughout all consumption. Additional GHG reductions due to negative rebound effect are also possible, for example in the case of solar energy solutions (Chitnis et al. 2013).
Collaborative consumption	Enabling and supporting collaborative consumption and sharing of GHG intensive resources is recommended.
Policy implications in the built environment	
New low-carbon strategies that are sensitive to area characteristics	General urban density policies may not be the most effective way to support sustainable built environment. It could be more effective to create new low-carbon strategies that are sensitive to area characteristics and allow participation. When residents can choose their own areas, reasons for and means of protecting the environment, they may be more committed to doing so. For example, there are suitable energy efficiency measures, local renewable energy production options and sustainable transport solutions for all types of areas.
Individuals	
	Instead of offering one model for all, we should have various examples of sustainable lifestyles.

5.3 Evaluation of the research

The thesis is based on quantitative analyses with high-quality secondary survey data. Secondary data refers to data not specifically collected for the purpose of the study. The main research materials consisted of the Finnish National Travel Survey 2010–2011 and Statistics Finland’s Household Budget Survey 2012. The total sample sizes consisted of more than 10 000 persons and 3 500 households, respectively. Both datasets include weight coefficients to correct the samples so that they are more representative of the Finnish population. These weights were employed throughout the thesis. Questions regarding the statistical representativeness of the studied groups and statistical significance are discussed in the papers. The papers also provide the p-values for the results of the thesis. However, the standard deviations, standard errors and confidence intervals have not been presented in the articles due to space limitations. The standard errors for the mean carbon footprints were in the order of magnitude of approximately 1–3% in most cases, and for the statistically significant regression coefficients they were in the order of magnitude of approximately 25–50%. To give an overview,

the mean carbon footprint in Finland is 9800 CO₂-eq, the standard error is 110 CO₂-eq, with 95% confidence intervals of 9600 CO₂-eq and 10 000 CO₂-eq, and the standard deviation is 6300 CO₂-eq.

The reliability aspects of quantitative research based on survey data include stability, internal and external reliability and inter-observer consistency (Bryman & Bell 2011). Stability means that the measuring procedure yields stable results when repeated many times. The stability of the carbon footprint model used in the thesis is high. Internal reliability needs to be considered if more than one measure is used to describe the same concept. It means that all of the measures being used should measure indeed the same issue. In Paper I, the direct GHG emissions were calculated using an entirely different approach than the one used to assess the carbon footprints in the other papers, i.e. by multiplying the VKT by the CO₂-coefficients. Also, the measure for urban structure was different in Paper I than in the other papers. Yet, the GHG emissions from driving and flying follow the same pattern as in the carbon footprint studies. This increases the reliability of the results. The absolute amounts of emissions were lower in Paper I, but this can be explained by the inclusion of direct tail-pipe emissions only.

External reliability means that the measuring procedure yields consistent results when used in different situations. In general, consumption-based assessments of energy requirements and GHG emissions yield similar results when applied to different populations (see Section 3.1). Inter-observer consistency means that the results are consistent between different observers. Here, the numbers are the same for everybody, but what lies behind the numbers is open to interpretation. The thesis is descriptive by nature and does not make strong causal claims. Thus, various theories can be presented to explain the carbon footprints. Rebound theory is not the only solution that can be used to explain variations in the allocation of expenditures. The thesis focuses on rebound theory because it forms a common denominator for all the studied mitigation measures and offers a plausible explanation for many of the observations.

Validity is concerned with the question of whether we are measuring what we think we are measuring. It includes face validity, concurrent validity and predictive validity (Bryman & Bell 2011). Face validity simply means that the measure is intuitively associated with the research concept. Concurrent validity means that the measure describes the research concept in question at the moment, whereas predictive validity means that the measure predicts the research concept. There are several concurrent and predictive validity issues in the thesis that must be considered. The main sources of possible systematic biases include the inherent problems of the EE IO analysis method, some uncertain and missing data in the model, and self-selection bias when comparing the carbon footprints. As discussed in Section 2.2, EE IO analysis includes the aggregation error and the assumptions of homogeneity and the linearity of prices. For these reasons, it is not a good method for assessing the carbon footprint of an individual, who may have very personal consumption habits. However, the method is suitable for studying the average carbon footprints of large groups of people. In a group consisting of many people, it is likely that a high variety of products are

bought from each consumption category, and the larger the group, the more the group's consumption patterns reflect average consumption patterns in general. This justifies the use of average GHG intensities. However, the homogeneity assumption is problematic when there are differences in prices between the studied areas, which is possible here. Similarly, it is problematic when there are differences in quality preferences between the studied groups. For example, people with high income levels are likely to prefer higher quality products and services than others (Girod & Haan 2010). Thus, the carbon footprint model used in the thesis may exaggerate the emissions of groups with high income levels somewhat.

The main concerns related to uncertain or missing data in the model have to do with the uncertainties regarding the emissions from the construction of buildings and missing data on public consumption. In the model, the emissions from construction are estimated by using a simple CO₂-eq coefficient per square metre of living space. This is likely to overestimate the emissions of detached houses compared to apartment buildings, since apartment buildings require more GHG-intensive construction materials and include common spaces (parking halls, staircases, etc.). However, the emissions from some types of public infrastructure, especially roads, are not included at all, which may favour low-rise and sparsely populated areas. These issues are discussed in detail in Paper II.

The self-selection bias is discussed in detail in Section 5.1. It arises from the use of cross-sectional data instead of panel or longitudinal data. For this reason, the thesis does not make any strong causal claims. The method used in the thesis cannot rigorously separate the effects (including rebound effects) of mitigation measures from the self-selection bias, that is to say, the inherent differences between the studied groups. Finally, the thesis is overall a static descriptive study of the situation as it is now. It has only a limited ability to predict how things will be in the future.

The focus of the research in Finland sets some limitations on the generalisability of the results, as described in the introduction of Paper II. However, the results on the high emissions from air travel for those living in the inner urban areas seem to be internationally relevant (Lenzen et al. 2004; Brand & Preston 2010; Holz-Rau et al. 2014), and the monetary-based trade-off between car ownership and air travel could partly explain the higher emission levels in other countries as well (Ornetzeder et al. 2008). However, motor fuel taxes are very high in Finland compared to other countries (Kossoy et al. 2015), which may partly explain the high rebound effect for giving up car ownership.

5.4 Recommendations for future research

More studies are needed to determine the overall environmental impacts of measures striving for sustainable built environment. Rebound effects need to be included in environmental assessments, since they affect significantly the outcome. While the study at hand aims at capturing these rebound effects, it has

some limitations that future research could overcome. These include the small scope in Finland, the inclusion of GHG emissions alone and the use of static cross-sectional data.

Rebound effects depend greatly upon place and time. Thus, it would be important to provide rebound studies around the world. From the perspective of urbanization, Global South would be especially interesting. Also technological development, changes in taxation and subsidies affect rebound effects (see e.g. Chitnis et al. 2014). Thus, timely and local research on rebound effects is continuously called for. Capital costs and embodied environmental impacts of investments should be included in rigorous rebound studies.

While the thesis focuses on GHG emissions, there are numerous other environmental impacts that are relevant in the built environment. Biodiversity, urban runoff, particulate matter pollution, material consumption and waste generation, just to name a few. For example Font Vivanco et al. (2014, 2015) have demonstrated that some environmental options may decrease one environmental impact but increase another.

Longitudinal datasets would be very valuable to study the causal relationships between environmental policies and actions and actual environmental outcomes. In the context of the built environment, the causal relationship between urban structure and travel behaviour has been broadly studied (see e.g. reviews by Mokhtarian & Cao 2008; Cao et al. 2009; Ewing & Cervero 2010). Carbon footprint research could use these studies as an example, and start to tackle the issue of self-selection. In the end, we could have rigorous causal studies that include the rebound effects for climate change mitigation measures in the built environment.

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We easily notice when others are not making the same sustainable choices that we are making, but do we notice when others are making sustainable choices that we are not? The thesis is a story about the fascinating and sometimes depressing carbon footprints of consumers in the built environment. The thesis illustrates via practical examples and empirical data how little people's total carbon footprints differ when people who have adopted various climate change mitigation measures are compared to people who have not adopted such measures. It is a horror story about how our efforts seem to run into the sand; but it has hope too, since some mechanisms are found that do reduce people's carbon footprints. The key concept of the thesis is the rebound effect.



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