Making the Transition to
a ‘Green’ Vehicle Fleet

An analysis of the choice and usage effects of incentivising the
adoption of low-emission vehicles

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“Dedicated to the more beautiful world our hearts tell us is possible.”
- Charles Eisenstein
Abstract:
Making the transition to a ‘green’ vehicle fleet is a noteworthy endeavour for any policy maker. Under the current global pressures of increasing greenhouse gas emissions there is no doubt that all efforts that can be adopted in order to improve the sustainability of our cities should be explored. In saying this however, it is crucial when designing such policies that proper cost-benefit analyses are performed; taking into account the potentially negative rebound effects of such measures and understanding which individuals are affected by such policies.

Comprising of two papers, this thesis analyses the choice and usage effects of an exemption for low-emission vehicles (LEVs) from Stockholm’s congestion charging scheme. The ambition of this study has been to understand: the extent to which this exemption policy influenced the demand for LEVs; which individuals were targeted; whether the policy led to any rebound effects (increased LEV usage); and ultimately what the effect of this policy was in terms of changes in emissions.

Paper I employs a MNL model to examine the demographics of those individuals who purchased an LEV in Stockholm during 2008 and the extent to which the exemption policy influenced this demand. It was found that those owners living within the cordon but who commuted across the boundary for work had the highest propensity towards purchasing an exempt LEV. The exemption policy was found to have increased the share of exempt LEVs by 1.9% to 18.9% in total, corresponding to an additional 550 exempt LEV purchases in 2008 due to this policy.

In Paper II, the differences in annual usage rates between demographically-similar LEV and conventional vehicle owners are calculated using propensity score matching in order to control for potential self-selection effects. Through this procedure it was found that the direct emissions of vehicle owners who adopted LEVs were reduced by 52.4%. Although the exemption policy was partially responsible for increasing the number of LEVs, it also appears to have encouraged an increase in annual usage, leading to rebound effects that offset the potential reduction in emissions (increase in LEV usage: 12.2% for owners that lived inside / worked outside cordon; 8.5% for owners that lived outside / worked inside cordon).

Through the analysis detailed in the two papers of this thesis, the effects of an incentive based policy in Stockholm upon both the demand and usage of LEVs have been highlighted. The benefits, as well as the possible complications of this initiative have also been discussed, in the hope of enlightening policy makers to ensure that potential emissions reductions are maximised for similar policy initiatives in the future. With personal vehicles likely to continue dominating the share of home-work trips over the coming years, cities must continue their efforts in encouraging the transition to a ‘green’ vehicle fleet. It is important, however, that these efforts lead to incentive based policies that are balanced, reasonable, and designed to minimise potentially substantial rebound effects.
Sammanfattning:

Övergången till en "grön" fordonsflotta är en betydelsefull strävan för samtliga beslutsfattare. När de globala utsläppen av växthusgaser ständigt ökar råder det ingen tvivel om att samtliga åtgärder som kan bidra till en hållbar utveckling bör implementeras. Vid utformandet av sådana åtgärder är det dock viktigt ordentliga kostnads-nyttoanalyser utförs, så att hänsyn tas till potentiellt negativa "rebound" och föreställe ås för vilka individer som påverkas.

I två artiklar analyserar denna avhandling effekterna på val och användning av ett undantag för fordon med låga utsläpp (LEV) från Stockholms trängselskatt system. Ambitionen med denna studie har varit att förstå: i vilken utsträckning detta undantag i politik påverkade efterfrågan på LEVs, vilka personer som den riktade sig till, om politiken lett till några "rebound" effekter (ökad LEV användning), och slutligen vad effekten var i termer av utsläpp.

Artikel I använder en MNL modell för att undersöka demografin av de personer som köpt en LEV i Stockholm under 2008 samt i vilken utsträckning undantaget påverkade denna efterfrågan. Det konstaterades att de ägare som bor inom avspärrningen men som pendlade över gränsen hade den högsta benägenheten att köpa en undantagen LEV. Undantagen från trängselskatt visade sig ha haft en väsentlig inverkan på efterfrågan på undantagna LEVs, andelen av dessa fordon ökade med 1,9% till 18,9% totalt eller ytterligare 550 LEV inköp under 2008.

I artikel II beräknas skillnaderna i årlig användning mellan LEV och konventionella fordon med demografiskt liknande ägare genom "propensity score matching" i syfte att kontrollera för potentiell självsvalselektion. Genom detta förfarande fanns de direkta utsläppen från fordonsägare som övergått till en LEV ha minskat med 52,4%. Även om undantaget från trängselskatt var delvis ansvarigt för att öka antalet LEVs verkade det också ha uppmuntrat en ökad årlig användning, vilket ledde till "rebound" effekter som motverkade den potentiella utsläppminskningen (ökning i LEV användning för ägare som åkte över gränsen vare 12,2% för dem som levde inom och 8,5% för dem som bodde utanför).

I denna avhandling har effekterna av en incitament baserad politik i Stockholm på både efterfrågan och användning av LEVs lyfts fram. Fördelarna liksom de möjliga komplikationerna av detta initiativ har också diskuterats i hopp om att upplysa beslutsfattare så att de potentiella utsläppsminskningarna från liknande politiska initiativ i framtiden kan maximeras. Personliga fordon kommer sannolikt fortsatt domineras andelen hem-arbete resor under de kommande åren och det är därför nödvändigt att städerna fortsätter sina ansträngningar förberömvärd att uppmuntra övergången till en "grön" fordonsflotta. Det är dock viktigt att dessa ansträngningar leder till incitament baserad politik som är balanserad, rimlig och utformade för att minimera de potentiellt betydande "rebound" effekter.
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Finally, I would like it noted that the hypocrisy in researching sustainable transport issues, whilst working at two universities on opposite sides of the planet, simply speaks for itself. It is for this reason that I choose to monitor the emissions directly related to my research activities, offsetting 100% of these emissions through carbon credits; and have adopted vegetarianism in order to minimise my own person emissions and do my small part for improving the sustainability of this special planet. After all, we only have one earth, so we all must consider what we can do differently to protect it. What’s the point in researching any issue related to sustainability, if in the end it’s your own research activities that are ultimately unsustainable?

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Stockholm, September 2013
Jake E. Whitehead
List of Papers:


Table of Contents:

Abstract: ...........................................................................................................v
Sammanfattning: ............................................................................................vii
Acknowledgements: ................................................................................... ix
List of Papers: ............................................................................................. xi
List of Figures: ............................................................................................ xv

1. Introduction ..........................................................................................1
2. Previous Research ..................................................................................4
   2.1 Analysing the demand for low-emission vehicles .....................5
   2.2 Analysing the usage of low-emission vehicles .................6
       and the potential for rebound effects .................................6
3. Case Study - Stockholm .....................................................................8
4. Research Questions and Methodological Concept .....................10
5. Data Source ..........................................................................................13
6. Main Results .........................................................................................14
   6.1 Main Results of Paper I ...............................................................14
   6.2 Main Results of Paper II ...............................................................15
7. Conclusions ..........................................................................................17
8. Future Research ....................................................................................18
9. Papers ....................................................................................................19
   9.1 Paper I – The impact of a congestion charging exemption
       scheme on the demand for low-emission vehicles ............19
   9.2 Paper II – Transitioning to low-emission vehicles: an
       analysis of the potential rebound effects and subsequent
       impact upon emissions .................................................................20
10. References ............................................................................................21
List of Figures:

FIGURE 1 - Timeline of low-emission vehicle sales in Stockholm, with various incentive policies annotated (38)..........................9

FIGURE 2 - Vehicle Alternatives including policies applicable in Stockholm in 2008 ..........................................................10

FIGURE 3 - Critical components to analysis of LEV ownership and usage.................................................................11
Making the Transition to a ‘Green’ Vehicle Fleet

"We can’t solve problems by using the same kind of thinking we used when we created them."
- Albert Einstein

1. Introduction

Transportation is one of the highest contributing sectors of global greenhouse gas (GHG) emissions and thus plays a significant role in the triggering of global warming, and in turn, potentially catastrophic climate change related weather events (1, 2, 3). The transport sector accounts for 14.4% of emissions in Australia (4), 23% in the UK (1) and is as high as 56.8% in Sweden (5). Since the transport sector is the fastest growing source of GHG emissions (6), at the current rate, transport emissions are expected to triple 2007-levels by 2030 (7).

In many countries around the world various initiatives have been introduced in attempts to reduce the environmental impacts of the transport sector. These policies have included: travel demand management (congestion-charging), low-emission vehicle rebates, alternative fuel subsidies and increased fossil fuel taxes. One of the more prevalent approaches to reducing greenhouse gas emissions within the transport sector has been to incentivise the purchase of low-emission vehicles (LEVs). Whilst having the advantage of lower rates of emissions and, in some cases, more efficient fuel consumption, LEVs also come with the downsides of: higher purchasing costs; lower fuel availability; and potentially also limited capabilities, such as limited driving range. In order to overcome these potential negative points for consumers, incentives such as: purchase rebates, tax reductions, and exemptions from tolls and parking fees, have been used in some parts of the world.

As a leading city in regards to sustainable development, Stockholm has implemented a number of different policies in order to reduce transport emissions. Principal amongst these was that of the congestion charging scheme. This policy involved charging motorists a time-varying tax for entering and/or exiting an inner-city cordon. It was originally justified by its projected reduction in greenhouse gas emissions by placing a cost on the externalities of every day private travel for motorists in order to encourage individuals to minimise their travel during congested periods of the day; and to choose more environmentally-friendly modes of transport. This policy was combined with an exemption from this charge for certain types of LEVs to encourage a transition towards a ‘green’ vehicle fleet in Stockholm. More details about these policies, and other similar incentives, are provided in the case study of Stockholm in Section 3 of this thesis.
It was this specific combination of policies that brought about an interesting situation where, although both policies shared the aim of reducing greenhouse gas emissions, the exemption for LEVs carried the risk of diminishing the effectiveness of the congestion charging scheme. As the number of vehicle owners making the choice to transition to an LEV increased, as a result of this shift, the total congestion-reduction effectiveness of the charging scheme in turn decreased and was weakened. As a result, congestion levels would increase, and despite a larger share of LEVs within the fleet, the situation would still result in greater congestion levels, than had there been no exemption at all, leading to conventional vehicles operating less efficiently and, in turn, emitting more (8). In fact, policy makers recognised that this potential issue was coming to fruition soon after the introduction of these two initiatives, with a significant spike in the demand for LEVs. As a consequence, the exemption policy was phased out less than 18 months after its introduction in order to rectify this issue.

Although it appears that policy makers did successfully recognise the significance of the negative effect that the exemption had upon the congestion-mitigation capabilities of the scheme, it is not as clear as to whether they managed to recognise another potentially negative factor at play, due to this combination of policies. With lower overall operating costs due to the increased fuel efficiency of LEVs, as well as an exemption from the cost of the congestion toll, this combination of policies also held the risk of leading to substantial rebound effects, where LEV owners would drive further than they would have done, given they had owned a conventional vehicle instead. These increased rates of usage in turn could have offset the originally intended reduction in emissions (9, 10).

It is this extremely distinct situation that has led to the production of this thesis in which the outcomes of introducing this combination of policies has been investigated through two papers detailing an analysis of the choice (Paper I) and usage (Paper II) of low-emission vehicles in Stockholm during 2008. The main ambition of this thesis has been to understand to what extent the congestion charging exemption influenced demand for LEVs; which individuals were targeted; whether the policy led to unexpected rebound effects (increased LEV usage); and ultimately what the overall effect of this policy, and the transition to a ‘green’ vehicle fleet, had upon the sustainability of Stockholm’s transport sector in terms of changes in greenhouse gas emissions.

In Paper I, the demographics of private individuals living and working in Stockholm county, who purchased LEVs during 2008, were examined. A multinomial logit (MNL) model was constructed based upon vehicle registration data that was merged with demographic data collected for each vehicle owner. The main contribution of this paper was to design a model through which the key factors influencing the decision to purchase an LEV at the time could be established, whilst allowing for an estimation of the effect that the exemption from the congestion charging scheme had upon the demand for LEVs. It should be noted that although
other studies have previously investigated private individuals’ purchasing behaviour in regards to LEVs (using stated-preference surveys), this paper details the unique opportunity provided to take a retrospective view on this problem by analysing revealed preference data of individuals who actually purchased LEVs in Stockholm during 2008; whilst providing details on the extent to which an incentive based policy influenced this demand.

Following on from the first study focussing on LEV choice, Paper II focuses on analysing the reported annual usage of LEVs by private individuals in Stockholm county during 2008. Using propensity score matching, the usage rates of demographically similar individuals i.e. similar age, income, etc., were compared, controlling for self-selection bias and any other demographic differences that could contribute towards differences in usage, with the only specified difference being whether individuals owned an LEV or not. The main contribution of this paper was to explore the potential rebound effects inherit with encouraging the transition towards environmentally-friendly products, as shown in other cases (11, 12, 13). Through this process the differences in emissions due to the transition to LEVs were quantified, and an attempt was also made to ascertain the effect of the congestion charging exemption policy upon LEV usage. Although a number of vehicle usage studies do exist, there is limited literature pertaining to the use of LEVs, and as such, Paper II aims to fill this gap, whilst providing useful insight for policy makers when considering the potential rebound effects of future incentive based policies designed to encourage the transition towards a ‘green’ vehicle fleet.

The dataset utilised in both papers was sourced from Sweden’s Central Bureau of Statistics (SCB) and contained Swedish vehicle registration data merged with the respective demographic information pertaining to Swedish vehicle owners. The data was restricted to vehicles registered and used within Stockholm country during 2008. As will be described in greater detail later in both Sections 4 and 5, the nature of the data did not allow for simultaneous analysis of vehicle choice and usage since all newly-purchased vehicles within the dataset did not contain real values for annual usage. It was for this reason that the choice of purchasing a new LEV in 2008 was analysed first, as detailed in Paper I. Subsequently, the usage of all LEVs with non-modelled values in the dataset – that were also in use during 2008 – were analysed through a separate investigation, as detailed in Paper II.

This thesis continues by providing further details regarding prior research in this subject field; the background to the relevant case study; the methodological concept and research questions adopted for both papers; along with the main results and conclusions, summarised for the entire investigation. This document concludes with notes on potential future research directions.
2. Previous Research

In recent years, as issues around global warming, climate change and energy independence have gained the public’s attention, in an attempt to address this issue in terms of the transport sector, many cities around the world have introduced different policies to encourage the transition towards a ‘green’ vehicle fleet. By reviewing the current literature in this subject field, the shear diversity and number of cities involved in this transition becomes blatantly clear. Papers range from analysing tax incentives for manufacturers of “eco-car’s” in Thailand (14); to increasing the psychological acceptance of electric vehicles (EVs) in Germany (15); to the potential for large registration tax rebates for alternatively fuelled vehicles in Denmark (16); and the various tax credits and highway lane priorities to encourage the adoption of hybrid vehicles (HVs) in the United States of America (17, 18, 19).

The variety of policies around world makes it difficult to assess the demand and usage of ‘green’ or low-emission vehicles as the definitions adopted for this category of vehicles vary significantly across policies. This is not just in regards to the number of terms used such as ‘clean’, ‘green’, ‘low-emission’, ‘energy-efficient’, ‘hybrid’ or even ‘environmentally-friendly’ but also the fact that some countries still define petrol and diesel models as ‘green’, whilst others restrict this category to only alternatively-fuelled models. There is also the added complication that in some countries, such as Sweden, the definition has varied over time, and at certain periods has been specified differently by different government agencies or differently for different policies. For example, the congestion charging exemption in Stockholm only applied to alternatively-fuelled LEVs, whilst the national government’s purchase rebate applied to all LEVs, including low CO\(_2\) petrol and diesel models, and this is despite both policies being implemented through federal legislature. Despite the complications of these varying definitions, what is clear from the literature is that a substantial number of cities around the world are trying to implement this transition through these various policy approaches.

What is also apparent is that without incentive-based policies, a significant increase in the demand for LEVs would not be possible (20, 21). Taking into account the overall success of this diverse pool of policies, what can be said is that the most successful approaches have included incentives, including cash payments, tax rebates, toll exemption, etc., that have outweighed the typical disadvantages of adopting a low-emission vehicle: i.e. lower driving ranges; smaller vehicle size; reduced engine power; limited fuel availability, etc. In countries where adoption rates of LEVs have been substantial, other policies have also been introduced in attempts to overcome some of the logistical disadvantages of the typical LEV, including: the mandatory supply of alternative fuels (for stations selling more than 3 million litres of fuel per year in Sweden), electric charging stations at parking locations, etc.
In addition to the previous research into different policy approaches for increasing the demand for LEVs, the two following subsections of this thesis detail previous research in regards to analysing both the choice and usage of low-emission vehicles, as well as literature pertaining to the rebound effects of encouraging transitions towards ‘environmentally-friendly’ products.

2.1 Analysing the demand for low-emission vehicles

In regards to modelling the demand for low-emission vehicles, several studies can be found examining this issue around the world (16, 17, 19, 20, 21). In each of these studies the principal approach has involved carrying out a stated-preference survey through which a number of hypothetical scenarios and questions were presented to respondents. These hypotheticals involved different types of LEVs and various policy incentives, in order to try and ascertain what approaches would be most successful in encouraging the adoption of these vehicles. After completing the survey, the data was then analysed to identify which variables were the most significant. The greatest limitation of these studies has been that the stated-preferences analysed did not necessarily reflect what individuals would have actually done. As such, although these studies do provide some insight into the issue, they fail to address what individuals have actually done around the world. Nonetheless, it was still interesting for the purpose of this investigation to explore what others have found through this stated-preference approach.

Both Bately et al. (20) and Ewing & Sarigöllü (21) found that their variables for the performance, as well as the initial cost of LEVs, were the most significant factors affecting demand for these vehicles. Similarly, Bunch et al. (17) found that the most significant variable in their data was that of the vehicle’s driving range. Mabit & Fosgerau (16) found that if the cost and performance of alternatively-fuelled vehicles (AFVs) and conventional vehicles were equal, due to environmental preferences in Denmark, AFVs would be selected.

Although these findings were interesting, as mentioned previously, the literature still fails to provide answers as to which owners have actually purchased LEVs, and what effect incentive based policies, such as the exemption for LEVs from Stockholm’s congestion charging scheme, have had upon the demand for these vehicles. By using revealed preference data in both Papers I and II, the principal shortcomings of stated-preference data analysis have been overcome, making these two papers unique amongst the current literature in that they explore the actual choice and real usage of LEVs and, whilst providing findings on the effect of an incentive based policy.
2.2 Analysing the usage of low-emission vehicles and the potential for rebound effects

With the adoption of low-emission vehicles as a recently new phenomenon, there is limited literature examining the actual usage rates of LEVs. As stated previously, the main studies pertaining to LEVs involve stated-preference data where hypothetical choices of individuals have been analysed. Paper II is unique amongst the literature as it provides an analysis of actual LEV usage and the effects of an incentive based policy upon this behaviour. It is through this strength that realistic conclusions can be made in regards to the issues addressed in this study.

The potential existence of rebound effects due to the transition towards LEVs is one of the principal issues examined in Paper II. So what are rebound effects? In the case of this study, rebound effects refer to increases in the usage of LEVs due to the improved fuel economy of these vehicles and a subsequent reduction in the cost per kilometre of driving. In saying this, rebound effects have been found to occur in the transitions to a wide-range of ‘environmentally-friendly’ products, including space heaters, washing machines, etc. (11, 12, 13). It is not the existence of such effects that is critical, but more so the extent to which these effects offset the intended aims of policies, that is important for policy-makers to be aware of.

The concept of rebound effects was first noted by William Jevons in 1865 (often referred to as Jevons’ Paradox) where he speculated that improvements in engine technology not only led to an increase in the efficiency at which coal was used, but made coal an economical fuel for many other uses and in turn led to an overall increase in coal usage (22). A similar concept proposed by Brookes (23) and Khazzoom (24), which is often referred to as the ‘Khazzoom-Brookes Postulate’ (25), suggests that policies promoting increases in energy efficiency lead to overall increases in energy usage, offsetting the intended policy-induced reductions.

Focussing specifically on the transition towards LEVs, it is unclear as to the extent to which such potential rebound effects have offset intended emissions reductions. In a recent opinion piece published in *Nature*, Gillingham et al. suggest that the rebound effects of such transitions are ‘overplayed’ and that although they are real, a number of studies have shown that these effects only offset energy savings by 5-30%, meaning that overall energy use is still substantially reduced through the transition towards more energy efficient products (26). Although not specific to LEVs, a number of studies have investigated the effects of increases in fuel economy or fuel efficiency upon vehicle usage. Green found that the rebound effects of these shifts have been consistently small, at around 5-15% (27). Similarly, Small & Van Dender (9) found that increases in fuel efficiency in the United States between 1966 and 2001 led to rebound effects of 5-20%, with a noticeable decline in the magnitude of these rebound effects over time.
One study that shares similar aims to those of this thesis, investigates the so-called ‘Prius Fallacy’ – the notion that transitioning to environmentally-friendly products results in increased energy usage that completely offsets any reduction in energy usage (28). The study compares the distribution of annual distances travelled by Prius owners in California with that of all vehicles between 2002 and 2009, using a dataset supplied by Gillingham (25). What is surprising about this study is that it found no discernible difference in the usage rates between Prius owners and the rest of the population. Given the literature discussed previously, this finding seems to be contrary to the general finding that rebound effects do occur in such transitions, even if these effects are deemed to be relatively minor. This discrepancy could be due to a number of reasons. Firstly, it appears that the analysis performed was rather simplistic and did not completely control for potential self-selection bias. Secondly, only a specific sub-sample of Prius owners were analysed and it is unclear as whether this also had some bearing on the unexpected findings. As will be discussed later in this thesis, Paper II specifically employs propensity score matching to control for any systematic differences in demographics i.e. self-selection bias, that could skew the true differences in usage rates between LEV and conventional vehicle owners.

Looking into more general literature pertaining to the modelling of vehicle usage, although not specific to LEVs, there are several studies detailing complex ownership and usage models. In a number of papers, Golob (29, 30, 31) employs structural equation modelling (SEM) to examine latent variables and the causal relationships between variables. Due to the nature of the data used in this study, although Golob’s approach was seen as potentially useful, it was not possible to analyse vehicle choice and usage simultaneously. More generally, SEM would have been useful for capturing preferences towards the environment, however, it was not seen as the most suitable method to adopt in order to control for potential self-selection bias i.e. where a certain demographic group chose to purchase LEVs and then use them in a particular way. For these reasons, it was decided that in order to answer the research questions of this study, whilst controlling for potential self-selection bias, it would be more appropriate to adopt the method of propensity score matching (PSM).

Propensity score matching is a method through which the annual usage of LEV owners could be compared with that of the annual usage of conventional vehicle owners, whilst controlling for demographic differences, in order to understand how the behaviour between these two groups differed. Although a much simpler approach to comparing the two groups could have involved comparing the mean annual distances travelled between the groups, in doing this, the analysis would not control for the potential of self-selection bias. By simply comparing the mean usage of each group, the difference in usage could not be solely attributed to the difference in vehicle types i.e. owning an LEV or not, as a number of other demographic differences would also influence the result.
By adopting PSM, these potential self-selection effects could be controlled for, by comparing each treated observation (LEV owners) – in this case the treatment being to own a LEV – with demographically-similar control observations (conventional vehicle owners). In doing so, this process essentially meant that owners being compared were of similar age, number of children, income, etc., with the only difference being whether they owned a LEV or not. Of course, PSM can only control for the demographics that are supplied and that are available, and as such, some other factors may have influenced the differences in usage, however, this method at least minimises the number of influencing factors.

Propensity score matching is a relatively common method that has been employed in a wide range of studies, in many different fields, particularly when analysing situations where self-selection bias could be present. In terms of transport research, one study that has adopted PSM is that of Cao, Xu, & Fan (32), in which they examine the effects of home location upon annual distances driven using calliper matching. Using this method, by controlling for demographic differences, this study was able to determine that house location did significantly affect driving behaviour. This is just one simple example of how PSM has been used in the transport sector to identify factors influencing vehicle usage.

3. Case Study - Stockholm

The city of Stockholm has long been renowned as one of the most sustainable cities on the planet. Through several environmental programs, policy makers have pushed sustainable development in the fields of waste management, recycling, eco-labelled electricity and, of course, clean vehicles. These efforts culminated in the city being awarded the European Green Capital title for 2010 (33). Focussing on clean vehicles, Stockholm has had a LEV project in place since 1994, promoting the adoption and usage of these vehicles, along with the associated fuel types (34). Between 1994 and 2005, several steps were taken to gradually push for a shift in the supply and demand of LEVs. Two of the main initiatives implemented during this period included replacing conventional vehicles in the government fleet with LEVs and introducing tax incentives to increase the demand for alternative fuels.

It was largely from 2005 onwards that the demand for LEVs in Stockholm started to grow substantially. This significant shift within the market can largely be attributed to a number of financial incentives that were introduced during the same time period. In May of 2005, free residential parking was introduced for inner-city residents with alternatively-fuelled vehicles, followed shortly by the introduction of a seven-month long congestion charging trial starting in January 2006, in which alternatively fuelled vehicles were exempt; the congestion charges became permanent starting in 2007.
The next significant policy to be introduced was that of the 10,000 SEK (1,000 EUR) National Government purchase rebate for all alternatively-fuelled and low CO₂ petrol/diesel vehicles in April, 2007. This last policy expanded the definition of low-emission vehicles to include not only alternatively fuelled, but also petrol/diesel vehicles that emitted less than 120 grams of CO₂ per km (34, 35). It was the combination of these three policies that led to a significant increase in the demand for LEVs within Stockholm. Figure 1 shows the number of LEV purchases, along with the introduction of these various policies. Additionally, a breakdown of the vehicle types that these three policies applied to is shown in Figure 2.

As mentioned in the introduction of this thesis, shortly after the implementation of the congestion charging scheme and the exemption from this charge for LEVs, policy makers realised that, at least in the long-run, the toll exemption would reduce the congestion-mitigation effectiveness of the scheme as a ballooning share of new vehicles purchased became eligible for the exemption (36). Ultimately, the exemption was phased out; such that LEVs registered from the 1st of January, 2009, paid the tolls and the exemption for older LEVs expired on the 1st of August, 2012 (35). The residential parking exemption was also phased out on the 1st of January, 2009, and the National Government purchase rebate was transformed into a reduction in registration taxes in July of 2009 (37).

**FIGURE 1 - Timeline of low-emission vehicle sales in Stockholm, with various incentive policies annotated (38)**

![Timeline of low-emission vehicle sales in Stockholm](image)
4. Research Questions and Methodological Concept

Before discussing the methodological concept behind this thesis, it is important to understand exactly what questions this study aimed to answer. These research questions provide a concise overview of what was the intended direction of this investigation. The main research questions of this study included:

- **RQ1**: Which individuals chose to purchase a low-emission vehicle in Stockholm during 2008 based on demographics? (Paper I);
- **RQ2**: How did the congestion charging exemption affect the demand for LEVs in Stockholm during 2008? (Paper I);
- **RQ3**: After purchasing a low-emission vehicle, how did these owners use their vehicles compared with demographically similar conventional vehicle owners in Stockholm during 2008? Were there any rebound effects present? (Paper II);
- **RQ4**: How did the congestion charging exemption affect the usage of LEVs in Stockholm during 2008? (Paper II); and,
- **RQ5**: Overall, what was the effect on emissions in Stockholm during 2008 due to the transition towards ‘green’ vehicles within the fleet and to what extent were these reductions offset by rebound effects? (Paper II).
Based on these research questions, a methodological concept was developed. As previously mentioned in Section 2.2 of this thesis, although other methods exist for modelling car ownership and usage simultaneously, due to the limitations of the data analysed, a two-staged approach was chosen instead, thus the production of the two papers included in this thesis. Referring to Figure 3, this analysis investigated the relationships between four sets of variables: the owner-specific demographics (age, income, number of children, etc.); the type of vehicle the owners choose to purchase; how they used that vehicle and the effect of the congestion charging exemption policy upon both vehicle choice and usage.

This investigation directly addresses four of the five relationships exhibited in this problem. In Paper I, a discrete choice model (MNL) was used to determine which demographic variables were most significant in the decision to purchase a low-emission vehicle (and also the different types of low-emission vehicles) – relationship 1.

In Paper II, a similar process was followed to Paper I, however, with a simpler binary logit model, using a different subset of the dataset (due to the data limitations previously outlined), where the choice was between a conventional vehicle and a low-emission vehicle. The results of this logistic regression were then used to develop a propensity score, for matching demographically similar individuals and subsequently comparing the differences in vehicle usage between the two alternatives (LEV vs. Conventional Vehicles) – relationship 2.

The third and fourth relationships were addressed in both papers where attempts were made to analyse the effect of the congestion charging exemption policy upon both LEV choice (Paper I; relationship 3) and LEV usage (Paper II; relationship 4).

The fifth and final relationship outlined in Figure 3, is that of the effect of socio-demographics upon the usage of vehicles. Although this is indirectly analysed through the process undertaken in Paper II, a future study could use some form of continuous regression, structured equation or continuous-discrete extreme value model, with the same dataset or potentially panel data of congestion charging cordon boundary crossings, to verify the results of this study.

In the case of both papers, in order to quantify the effect of the congestion charging exemption upon both LEV demand and annual usage, an assumption was made that only those vehicle owners who commuted across the cordon boundary were affected by this policy. By making this assumption, although conservative, it allowed for an estimation of the policy effects through setting up an experiment where different vehicle owner groups could be compared based on whether they were affected or not by the exemption. Principal to this approach was the division of vehicle owners based upon home-work locations, in relation to the cordon boundary, in order to control for geographic differences affecting both LEV choice and usage, whilst separating out the effects of the policy based upon this division.
In both papers vehicle owners were effectively split into the four following groups:

A. Living and working within the cordon boundary;
B. Living within but working outside the cordon boundary (crossing);
C. Living outside but working within the cordon boundary (crossing); and,
D. Living and working outside the cordon boundary.

In Paper I, this division was replicated by including a variable for representing commutes across the cordon (used to estimate the utility benefit of the exemption policy), and another variable representing home location in relation to the cordon boundary (use to control for geographic differences in preferences towards LEVs). In Paper II, the dataset was split based upon the specification outlined above, with propensity score matching carried out separately for each of these four groups. By comparing the results of similar groups, with the only difference being whether they commuted across the boundary or not (Group A vs. Group B; Group C vs. Group D), the effect of the exemption policy on LEV usage was then estimated.

Although it would have been interesting to have been able to quantify the effect of the exemption policy on those vehicle owners that did not commute across the cordon boundary i.e. Groups A and D, this was not possible with the data supplied. Section 8 will detail future research directions, including one study using panel data that may be able to assess the effect of this exemption upon these other groups.
For more information regarding the specifics of the methodologies adopted in each stage of this investigation, please refer to the methodology sections of Papers I and II, included later in this thesis.

5. **Data Source**

The dataset used in the two papers of this thesis was acquired from Sweden’s Central Bureau of Statistics (SCB). It consisted of vehicle registration data for the year 2008 matched with socio-economic variables for vehicle owners in Sweden. This particular dataset is part of a larger set of panel data, which holds the same information but for the years 1998 through to 2008. In this investigation, data from 2008 was analysed as it was the only year in which the exemption policy was active for the entire 12 months, and as previous years had insufficient numbers of LEVs.

The base dataset was created by merging all vehicles with their respective owners, and disregarding any entries that either had no vehicle or no owner using *STATA 10*. At this stage, the dataset included all vehicle owners in Sweden, so it was filtered down to only include those individuals who both lived and worked within Stockholm county. In addition to this refinement, approximately 50% of the vehicles included were company-owned, -leased or commercial vehicles and since it was impossible to determine whether the respective home and work locations corresponded with the nominated owner, these entries were also dropped.

In Sweden, new vehicles are not required to report the annual distance driven through a safety inspection until 2-3 years after the date of purchase. Due to this legal occurrence, newly purchased vehicles were assigned a value for the annual distance driven in the dataset; however, this value was simply obtained from a model used for tax purposes and was not the true figure. It was due to this characteristic of the dataset that the investigation had to be split into the two stages so far described, being:

- Examining the vehicle choice for only newly purchased vehicles, registered and in use during the year 2008 (Paper I); and,

- Examining the usage of all post-2000 vehicles with real usage values, registered and in use during the year 2008 (Paper II).

It is due to this limitation that the two distinct subsets of the consolidated dataset, described above, had to be used for each of these papers. Ideally it would have been preferable to simultaneously analyse the choice and usage of only the newly purchased vehicles, however, this simply was not possible. It is also important to note that, in the case of Paper I, ‘newly purchased vehicles’ refers to all vehicles with a manufactured date of 2007, 2008, 2009, due to some 2007 and 2009 models being sold and registered during 2008.
6. Main Results

Through the two-staged approach adopted, a number of interesting results were obtained in both Papers I and II. These results are unique amongst the current literature in that not only do they produce findings based on revealed preference data, including the actual choice and real usage of LEVs, but that they also include the analysis of the effect of an incentive based policy – the congestion charging exemption – upon both of these components. The main results of each of these papers have been included in the following sub-sections of this thesis.

6.1 Main Results of Paper I

The analysis undertaken in Paper I not only provided results allowing for analysis of the common characteristics of individuals who chose to purchase an LEV in Stockholm during 2008, but also provided some insight into the differences in preferences towards the various different types of LEVs. The main ambition of this paper was to fill a gap existing in the literature in regards to analysing individuals who had actually purchased LEVs, and in turn, what the effect of incentive based policies had been upon this demand.

Focusing on the estimation results, a number of key variables stood out in determining an individual’s preferences towards LEVs. In answering RQ1, these included: home distance from the cordon boundary (negative), inter-cordon residency (positive) and crossing the boundary for home-work trips (positive). In terms of differences amongst LEV types, inter-cordon residents had the highest preferences towards electric vehicles and a trend was identified of younger individuals (under the age of 30) preferring low CO$_2$ vehicles, compared with individuals over the age of 30 preferring electric vehicles. From this investigation it was also found that low CO$_2$ vehicle owners did not appear to be affected by the congestion charge.

After analysing the estimation results, these values were then used to calculate the predicted shares and in turn, to quantify the effect of the congestion charging exemption upon the demand for LEVs in Stockholm during 2008 - answering RQ2. Overall, it was found that the exemption policy increased the share of exempt LEVs in Stockholm by 1.9% to a total share of 18.9%. The effect on the demand for LEVs was substantially stronger for those individuals commuting across the cordon boundary, with a 13.1% increase for individuals living inside of the cordon, and a 5.0% increase for those living outside of the cordon. This increase in demand corresponded with an additional 550 exempt LEVs being purchased in Stockholm during 2008 (out of a total of 5,500 purchased in the same year) due to the congestion charging exemption.
In summary, Paper I found that the congestion charging exemption did have a substantial effect upon the demand for LEVs in Stockholm during 2008. Unsurprisingly, the policy appears to have had the greatest impact upon those vehicle owners who crossed the cordon boundary for home-work trips. It also appears that there were some differences in the preferences towards different types of LEVs within Stockholm during 2008, most notably that those individuals living within or close to the city centre had the highest preference towards electric vehicles.

Through Paper I, results have been obtained showing the common characteristics of individuals who actually did purchase LEVs in Stockholm, and the effect one incentive based policy had upon this demand.

6.2 Main Results of Paper II

The results of Paper II provide some useful insights into another segment of the literature that is limited – that of how individuals who have purchased LEVs actually used their vehicles and whether rebound effects exist due to such transitions. It appears that this is one of the first studies to detail how individuals have used LEVs in a city where a number of sustainable transport policies targeting the demand for this specific category of vehicles have existed.

By analysing the results after the procedure of propensity score matching had been carried out, it appears that, on average, owners of LEVs drove substantially further than owners of conventional vehicles, answering RQ3. Focussing on the groups that crossed the boundary, for those living outside the cordon, but crossing the boundary for work, the difference in usage was 8.2%, whilst for the group of LEV owners living in the cordon but crossing to work outside, the difference in usage rates was 12.2%.

These findings, although in line with the wider literature pertaining to the rebound effects of transitions to “environmentally-friendly” products (11, 12, 13, 26), counters the findings of a similar investigation into the comparison of usage rates of Prius owners in California, with the rest of the population (29). As mentioned previously, this study found no discernible rebound effects due to this transition, but it is unclear whether the authors properly controlled for self-selection bias. It would be interesting to apply the method used in this paper to the data used in their study (25) to see whether different results would be obtained, and whether some rebound effects would instead be found.

Taking into account that all LEVs analysed in this stage of the investigation were exempt from the congestion charging scheme, it appears that a strong relationship existed between this policy and increased vehicle usage. In saying this, however, of course a number of other factors could have influenced this change in behaviour, and, as such, it was important to also analyse a group of vehicle owners that were not affected by the exemption policy in order to quantify this effect.
Referring to the results obtained for those vehicle owners living and working outside the cordon boundary, the difference in usage between LEV and conventional vehicle owners was 4.9%. This is interesting, as these owners were not affected by the congestion charging exemption, nor were they separately targeted by any other specific incentive based policy. This finding seems to suggest that another effect was potentially at play. Either owner’s felt that they had the right to drive further since they now owned a LEV or that the increase in usage was purely due to the decreased cost of using LEVs (improved fuel efficiency).

It is difficult to attribute a specific figure to the impact that the congestion charging exemption had upon LEV usage. By adopting PSM and analysing groups separately based on their home-work locations, this study does minimise the number of potentially unconsidered effects. Despite this, however, it is hard to know whether other factors also contributed to these changes in behaviour. For this reason, this study can only provide an upper limit on the potential effect of the congestion charging exemption on LEV usage. By taking the difference between those living and working outside the cordon, and those owners living outside but crossing the cordon for work, it can be said that the exemption increased LEV usage for this group of owners by up to 2.8% (up to 366.92 km per low-emission vehicle per year).

Similarly, by taking the difference between those living and working inside the cordon, and those owners living inside but crossing the cordon for work, it can be said the congestion charging exemption increased LEV usage for this group of owners by up to 8.5% (up to 1137.53 km per low-emission vehicle per year). These findings answer RQ4.

In order to better understand the potential repercussions of these findings for the sustainability of Stockholm county, the differences in CO₂ emissions were also calculated. This procedure was a simplistic analysis of a very complex issue, however, the purpose of this supplementary calculation was not to provide a definitive answer in regards to the actual impact of the congestion charging exemption upon GHG emissions, but instead to simply shed some light upon the extent of the potential impacts of the rebound effects discovered.

From this analysis it was clear that the rebound effects of increased LEV usage did have an impact upon the goal of reducing GHG emissions. Although emissions were reduced overall by 52.4% due to the transition to LEVs (assuming a conservative fuel mix scenario), this study found that emissions could have been reduced by a further 2.4% on average had these rebound effects not have been present. These results answered RQ5. It is also important to note that these offsets in emissions do not take into account the fact that increased LEV usage would have also led to increases in road congestion, which in turn would have decreased the efficiency of all conventional vehicles in the road network, and in turn increased the emissions of these vehicles even further. This is just one example of a secondary
effect of these rebound effects. It is difficult to quantify the exact impact of these secondary effects, but if the decision by policy makers to quickly phase out the exemption is any indicator, no doubt the substantial increase in LEVs also lead to a substantial increase in congestion levels within Stockholm’s road network.

These findings suggest that although emissions were reduced through a transition towards ‘green’ vehicles in the fleet, these reductions were partially offset by the rebound effects of increased usage by LEV owners. As to the specific reasons behind these rebound effects, this is a more difficult question, however, it does appear that the congestion charging scheme was responsible for some of this increase in usage, particularly for those owners who commuted across the cordon boundary for home-work trips.

Overall, Paper II details some very interesting results into the usage of LEVs and the effect that the congestion charging exemption had upon LEV usage. As studies into the usage of LEVs are very limited, these results form the basis of one of the first investigations into LEV usage in the literature, and will be useful for future comparative studies between Stockholm and other cities with similar shifts within their fleets towards ‘green’ vehicles into the usage and behaviour of LEV owners.

7. Conclusions

Making the transition to a ‘green’ vehicle fleet is a noteworthy endeavour for any policy maker. No doubt, under the current pressure of climate change and increasing global emissions, all efforts that can be made to improve the sustainability of our cities should indeed be carried out. In saying this, however, it is essential when drafting such policies, that proper cost-benefit analysis is carried out and that particularly the potential rebound effects of such policies are also taken into consideration.

As a self-declared champion of sustainable development, the last thing that the author of this thesis would want to do is to talk down the significance of making the transition towards a ‘green’ vehicle fleet. Rather, the purpose of the two papers of this thesis has simply been to highlight the effects of one incentive based policy in Stockholm upon both the demand and usage of LEVs, and to discuss the possible complications that need to be better addressed in order to maximise the potential greenhouse gas emissions reductions of such policy initiatives. Through this process, in Paper I, it was found that the exemption policy substantially increased the demand for LEVs within Stockholm, which was a positive policy outcome. A number of demographic variables were also identified as common characteristics of LEV owners and, as such, provide some insight into which individuals were affected, and/or targeted by the incentive based policies present in Stockholm during 2008.
In Paper II, it was found that the exemption policy reduced direct emissions of vehicle owners who adopted LEVs by 52.4%, quite literally a massive reduction, which was at least partially due to the congestion charging exemption. Despite this finding, although the exemption policy did increase the number of LEVs leading to this overall reduction in GHG emissions, the policy also appears to have encouraged an increase in LEV usage, offsetting the potential reduction in emissions. This increase in usage would have also led to the creation of additional congestion within Stockholm’s road network, leading to reduced efficiency for all other conventional vehicles, and in turn further increases in emissions, further offsetting these initial reductions in greenhouse gas emissions.

With a good chance that the personal vehicle will continue being a high share mode for home-work trips over the coming decades, cities around the world should continue their efforts in encouraging the transition towards ‘green’ vehicle fleets. It is important, however, that these efforts involve balanced, well targeted and reasonable incentive based policies. Furthermore, these policies must be designed to control for potentially substantial rebound effects, such as those outlined in this thesis, in order to minimise the possible negative impacts of such initiatives that could substantially offset intended reductions in greenhouse gas emissions.

8. Future Research

A future stage of this study involves analysing toll crossing data for the Stockholm congestion charging scheme; comparing two waves: one taken before the phase out of the LEV exemption; and the other taken after the phase out. Individual vehicle owners will be matched between the two waves of data, providing the opportunity to explore the behaviour of vehicle owners before and after the phase out of this significant incentive based policy. The data will also allow for a more general analysis of vehicle usage, providing the opportunity to verify some of the findings found in the two papers included in this thesis. These first two papers also did not consider vehicle pricing responses by vehicle manufacturers in response to government policies, which could influence vehicle purchase decisions. These vehicle pricing responses are currently being analysed in a separate and complementary effort, which is to be published as a third paper.
9. Papers

9.1 Paper I – The impact of a congestion charging exemption scheme on the demand for low-emission vehicles


To stimulate sales of Low-Emission Vehicles (LEVs) it was decided to exempt some of these automobiles from Stockholm’s congestion charge. In this paper the effect this policy had on the demand for LEVs is estimated by simulating different policy scenarios using the results of a multinomial logit model (MNL). This model was based upon owner-specific demographics merged with vehicle registry data for all new private vehicles registered in Stockholm county during 2008. Through this process the characteristics of individuals who had a higher propensity towards purchasing an exempt LEV were identified. The most significant characteristics included inter-cordon residency (positive), distance of home from cordon boundary (negative), and commuting across the cordon boundary (positive). Inter-cordon residents commuting across the boundary had the highest propensity towards purchasing an exempt LEV. Owners under the age of 30 preferred low CO2 petrol/diesel vehicles, whilst those over 30 preferred electric vehicles. In terms of electric vehicles, those living within the cordon had the highest propensity towards this alternative. By calculating vehicle shares from the MNL model, and comparing these with a simulated scenario where the congestion charging exemption was inactive, the policy was found to have a substantial effect, increasing the share of exempt LEVs in Stockholm by 1.9% to a total share of 18.9% (13.1% increase for inter-cordon residents commuting over the boundary; 5.0% increase for outer city residents commuting over the boundary). In other words, the exemption policy was found to have increased LEV purchases in Stockholm, during 2008, by approximately 550 vehicles.

The data analysis, modelling and paper writing was carried out by Jake Whitehead.
9.2 Paper II – Transitioning to low-emission vehicles: an analysis of the potential rebound effects and subsequent impact upon emissions


This paper examines the annual distances driven between demographically-similar, privately-owned low-emission vehicle (LEV) and conventional vehicle owners in Stockholm during 2008. This analysis was used to assess the potential rebound effects of using financial incentives to encourage a transition in the vehicle fleet from conventional vehicles to LEVs. The potential rebound effects and differences in emissions due to the transition have been estimated, along with an assessment of the effect of an exemption for LEVs from Stockholm’s congestion charging scheme, upon annual distance travelled. The analysis used vehicle registry data merged with owner-specific demographics, including home-work locations. A logistic regression was performed on these demographics to construct scores representing each individual’s propensity to purchase an LEV. These propensity scores were then used to match and compare the odometer-based distance travelled for demographically-similar LEVs and conventional vehicle owners. Rebound effects of 5-12% were identified in regards to the differences in annual distance driven between LEV and conventional vehicle owners, with those who commuted across the cordon boundary found to have the greatest differences suggesting that the exemption policy did increase LEV usage. Overall, it was determined that the direct emissions of LEV owners were reduced by 52.4% due to the transition to these vehicles. The findings suggest, however, that emissions could have been reduced by a further 2.4% if these apparent rebound effects had not occurred. Furthermore, this offset in emissions reductions did not include secondary effects, such as increased congestion, that would have led to greater emissions from conventional vehicles.

The data analysis, modelling and paper writing was carried out by Jake Whitehead.
10. References


