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# Spatial aspects of greenhouse gas emissions from transport demands by households in Trondheim

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# Abstract

The aim of this study was to explore the spatial variation in household greenhouse emissions from local transportation in Trondheim, the reasons for this variation, and explore scenarios of what bearing these variations might have on greenhouse gas emissions in the future. Data from a national travel survey was used together with modal emissions coefficients to model the average emissions per capita for 46 geographic zones in Trondheim. Linear regression was used to explain the variation in average emissions using a number of explanatory variables identified from the literature. The regression models explained around 75–80 per cent of the spatial variation in average emissions ($0.75 \leq \text{adj } r^2 \leq 0.79$), with centre distance explaining the majority of variation. Using a regression function containing centre distance and access to public transport as explanatory variables, five scenarios were constructed for emissions in 2030, which suggest that centralisation of new residential building developments and improvement in the public transport network could limit the growth in annual greenhouse gas emissions to approximately 10 per cent in the presence of approximately 30 per cent population growth.

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# 1 Introduction

## 1.1 Background

The global necessity to reduce anthropogenic greenhouse gas (GHG) emissions substantially in the coming decades is being undermined by the continuing increase in emissions from motorised transport, even in developed countries such as Norway, where the argument for GHG reduction strategies is well advanced in the policy sphere. Personal mobility is taken to be both a right and a necessity and emissions levels are particularly high in Norwegian towns such as Trondheim, despite the commitment of local governments to both local GHG mitigation policies and nationally administered schemes such as Cities of the Future. While technological improvements to transport technology are promising, it is widely accepted that a combination of fiscal, planning and technological measures will be necessary to reduce emissions from personal transportation. The focus of this study is how the spatial variation in land-use, urban form and socioeconomic variables affects transport emissions, and explore the possible importance of this spatial variation for decision-makers tasked with effecting emissions reduction policies.

## 1.2 Problem formulation

In an earlier study, the student used travel survey data with vehicle emissions coefficients to make a preliminary analysis of per capita GHG emissions in Trondheim, employing simple linear regression (with household distance from the town centre as the explanatory variable) and GIS mapping software (Loveland 2011). The results showed that at a highly aggregated geographical resolution the relationship between household distance from centre and per capita emissions was strong ($r^2$=0.773) but much less strong at a lower geographical resolution ($r^2$=0.123).

For this thesis, the spatial analysis developed in the previous project was be refined and expanded in order to answer the following research questions:

i) Is there a level of geographical resolution for average per capita emissions that is statistically robust yet analytically useful;

ii) Can explanatory variables other than centre distance be incorporated into a regression analysis in order to better explain the spatial variation in per capita emissions?

iii) What can scenarios of urban development Trondheim – specifically different settlement patterns resulting from the city's predicted demographic expansion – tell us about the impact of the variables examined in the regression analysis on GHG emissions levels in the future?

# 2 Literature Review

The literature review presented below draws on studies from many fields, including urban and planning studies, transport analysis, spatial analysis and geography. Transport patterns, travel behaviour and GHG emissions are phenomena that attract interest within many different academic disciplines, which is both challenging and beneficial for the researcher. Rather than dividing the review by academic discipline, a themed-approach will be taken. First the concept of urban systems will be introduced, and their relevance to climate change discussed. Secondly, the literature on urban form and travel behaviour will be considered, on the basis that variation in travel behaviour is one of the primary causes of variation in emissions from personal transport. Thirdly, an appraisal of existing studies of emissions from personal transport within urban systems will be made. Finally, the object of analysis in this study, Trondheim, will be presented and a review of the policy context undertaken.

## 2.1 Urban systems, transportation and greenhouse gas emissions

Cities and towns can be thought of as systems in the same way as other industrial systems within industrial ecology, with an inflow of energy and materials and an outflow of waste and emissions. Their importance as systems relevant to the challenge of achieving sustainability is considerable: cities are net importers of energy and materials (Brunner 2007) and it was estimated that more than two-thirds of global energy consumption in 2006 could be attributed to cities (Bader & Bleischwitz 2009). The challenge of cities for long-term sustainability is likely to increase, with a growing proportion of the world's population living in urban areas (Crossette 2011).

Despite the importance of urban systems for the global flow of energy and emissions, they have not been traditional objects of study within industrial ecology. Bai writes:

*Cities have not been major units of analysis in industrial ecology, and industrial systems are not of much interest to urban scholars. People who are concerned about cities and those who are concerned about industrial systems generally belong to different professional groups (Bai 2007).*

Yet in principle towns and cities are good candidates for study within industrial ecology and interest in urban systems has been growing in recent years. The methodological approach within industrial ecology that can be applied to the study of urban systems is that of metabolism: a city can be viewed in the same way as a complex organism with, firstly, a flow of energy and materials into the system, secondly, a an outflow of waste and emissions and thirdly a system of mechanisms, drivers and processes that regulate the flows into, within and out of the system (Bai 2007). In this study, a metabolism approach is taken to GHG emissions from transport, with the spatial variation of urban form and transport variables assumed to be acting as regulators and drivers of emissions.

A note here should be made on the scope of GHG emissions attribution taken when studying towns and cities. In GHG emissions accounting, a distinction is made between three scopes:

Scope 1: Direct emissions, i.e. all GHG that are directly emitted within the territory, such as stationary combustion, mobile combustion, process and fugitive emissions;

Scope 2: Indirect emissions which result as a consequence of activities of the territory such as emissions due to the generation of electricity, district heating, steam and cooling;

Scope 3: All other indirect and embodied emissions such as landfill or compost emissions. (Bader & Bleischwitz 2009)

This study focuses on Scope 1 emissions, and references to GHG emissions in this literature review can be taken to concern direct emissions unless stated.

Kennedy et al. (2009) undertook a review of the literature in order to examine how and why GHG emissions vary between cities from an industrial ecology perspective, finding that a balance of geophysical (climate and access to resources, for example) and technical (urban design and power generation) drive emissions levels. Regarding transport specifically, the study finds a strong inverse relationship, shown in Figure 2.1, between the overall population density of a city and its per capita emissions from transportation. Perhaps surprisingly no statistically significant link was established between average personal income and emissions from transportation in the 10 global cities studied by Kennedy et al.

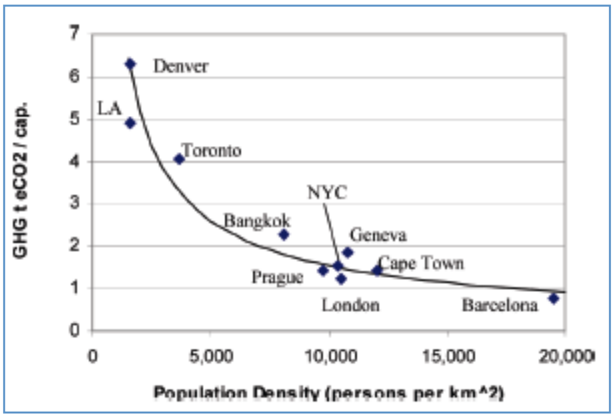


**Figure 2.1 The relationship between population density and transport emissions *(Kennedy et al. 2009)***

Globally, about a quarter of direct GHG emissions are attributed to transportation (Allwood et al. 2010) and in urban systems the share can be even higher. In Norway, emissions from transportation have increased by around 50 per cent since 1990 (Miljøstatus i Norge 2010), in contrast to other sectors such as industry where reductions have been achieved, and are now responsible for around half of emissions within Norwegian towns (Trondheim Kommune 2010a).

A key factor determining the level of urban emissions is the type of technology used for transportation: a bicycle produces zero direct emissions whereas the average car produces around 100–150 grammes of $CO_2$ for each kilometre travelled by a single person, on average (Toutain, Taarneby, and Selvig 2008). The International Panel on Climate Change states that “the most promising strategy for the near term [*in reducing transportation emissions*] is incremental improvements in current vehicle technologies” while at the same time acknowledging that technological change will not be enough to reduce GHG emission sufficiently, saying that "only with sharp changes in economic growth, major behavioural shifts and/or major policy intervention would transport GHG emissions reduce substantially." (Kahn Ribeiro et al. 2007, pp.335–336) The advantage of taking a metabolism approach to studies of urban systems is that both technological and structural determination of the overall systems behaviour in terms of emissions can be taken into account. In this study however the focus will be on the relationship of urban form – "the geographical distribution and density of the building stock and the urban functions therein" (Næss In press) – to travel behaviour and thus transport emissions.

## 2.2 Urban form and travel behaviour

Ultimately an urban system is a human settlement, and the GHG gas emissions from transportation within such systems will be determined by the travel behaviour of the individuals that live within that system. Travel behaviour is characterised by three linked factors – mode choice, trip frequency and trip distance – and the study of the relationship between travel behaviour and urban form provides a rich vein of literature and debate.

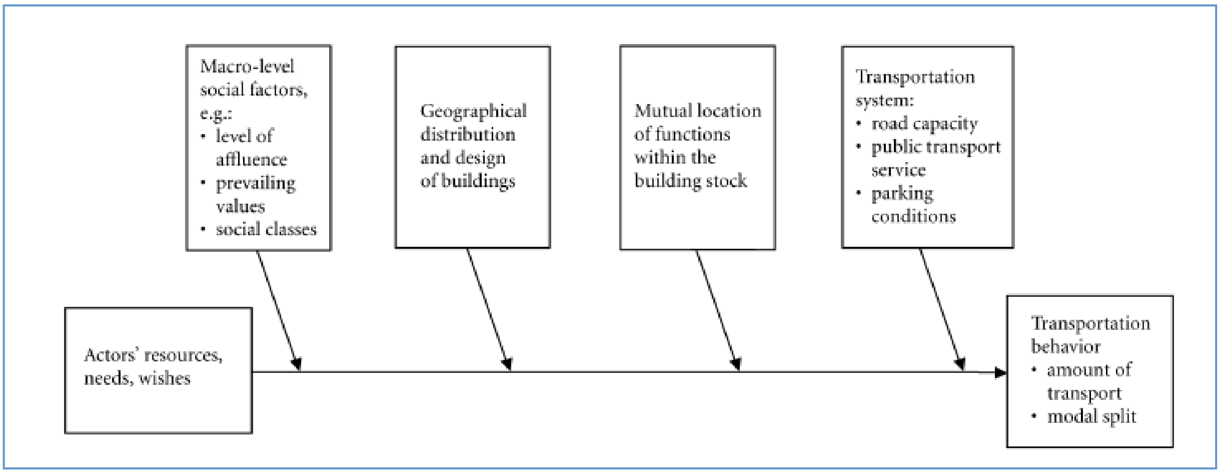


Figure 2.2 Transport behaviour as a function of land use characteristics and individual characteristics of the travellers
*Source: (Næss, 2004)*

The causal association between different urban form and land-use, socio-economic and attitudinal factors and travel behaviour is summarised in Figure 2.2, which is taken from a paper on the philosophical basis of transport analysis by the transport and planning academic, Petter Næss (2004).

The debate on the relationship between urban form and travel behaviour essentially polarises between those who believe urban form in the primary driver of transport behaviour and those who believe that the relationship is of a correlative rather than causative nature. A key early contribution from those in the former group came from Newman and Kenworthy in the late 1980s. In a much cited paper they showed that cities with a denser urban form tend to be more energy efficient in their consumption of transport fuel, and that fuel consumption per capita increases with distance from urban centre

(Newman & Kenworthy 1988). This finding has been confirmed and expanded upon by other studies (see Banister 1997 for examples) but challenged by others, who contend that the such findings are not statistically significant when controlled for socioeconomic and demographic factors (Boarnet & Sarmiento 1998; Ewing & Cervero 2010).

Næss is an advocate of the causative influence of urban form on travel behaviour, but acknowledges that the precise causative relationship between these different types of influences is a source of continued debate: "Because income levels, household structure, age and leisure interests of the inhabitants often vary between inner and outer parts of the city, there is a risk that differences in the transportation actually caused by such factors are being explained with differences in the location." (Næss 2006). Other studies have suggested that residents might choose their location based on their travel behaviour preferences, rather than their location determining their travel behaviour (Boarnet & Sarmiento 1998).

The continuing debate about the causative nature of the relationship between urban form and travel behaviour has led to a related debate on the effectiveness of land-use policies. Some have argued for greater centralisation of urban systems, on the basis that this will reduce overall travel demand, while others have argued that this will achieve little other than to restrict freedom of choice. Bannister and Hickman provide a summary of the nature of this debate:

> *There has been a healthy debate in the literature about the relationships (if any) between urban form and transport. Some have argued for the compact city or polycentricity, whilst others have suggested that continued dispersal will lead to a natural 'co-location' of residential and employment locations. There is certainly a continuous and dynamic process going on, which results in centralisation and decentralisation, as people and jobs are located in response to each other and other factors. In all cases (ironically) the aims are much the same, namely to reduce average journey distances, trip frequencies, traffic volumes, energy consumption and/or transport emissions. (Banister & Hickman 2006)*

In the Nordic context greater weight has been put on the influence of urban form on travel behaviour than in the American and British literature, according to Næss (In Press).

In terms of distance of residence to urban centre, (Synnes 1990) showed that residents of Trondheim showed longer average travelling distances the further they lived from the centre. Næss, Røe and Larsen (1995) found that residents in the outer districts of Oslo travelled further each week by motorized transport in a study of 30 different suburbs. In a study of 22 Nordic towns, energy use for transport was found to reduce with average distance to centre from residential location (Næss et al. 1996). In a more recent major study of Copenhagen Næss found that residents living further from the city centre travelled further using motorized transport, had longer commuting distances and travelled more at weekends (Næss 2006; Næss 2009).

Several Scandinavian studies found that the density of the residential area itself (rather than the town overall) also affects travel behaviour. For example (Næss et al. 1995) found that high density of dwellings leads to a greater share of travel by pubic transport. However, other studies have found that neighbourhood density is not significant if controlled for centre distance (see Næss, In Press for a full review).

Although the influence of socio-economic and demographic factors on travel behaviour are not the main focus of this study, it is worth devoting some space to this topic as some researchers have contended that these factors have more of a bearing on travel behaviour than urban form variables (Ewing & Cervero 2010). (Boarnet & Sarmiento 1998) make that point, and also find that household income is a significant predictor of travel behaviour, with higher income households travelling more. (Dieleman et al. 2002) found that household with a high income were more likely to own and use a car in their study of Dutch travel survey data, as were families with children. Ryley (2006) also found that the addition of children to a household increases car dependency. Age has also been found to influence travel behaviour, with a Canadian study finding that elderly people make fewer trips after retirement, but a greater proportion of trips by car (Newbold et al. 2005). Employment status is also found to be a predictor of transport behaviour in some studies (Curtis & Perkins 2006). In his review of energy consumption from transport in 22 Nordic towns, Næss found that educational status was a significant variable: towns with a higher percentage of blue-collar households showed higher energy use-from transport. For a full review of socio-economic variables' influence on travel behaviour, see Curtis and Perkins (2006)

## 2.3 Residential greenhouse gas emissions from transport

As noted above, the variables describing travel behaviour in most studies are mode choice, trip frequency and travel distance, the latter two often being combined into vehicle-miles-travelled (VMT). By either using energy-per-distance coefficients or fuel-use data, it is possible to take a different perspective: “Energy-use measures combine all the characteristics of travel (mode, distance, and frequency), together with occupancy, to give a new set of composite measures of travel.” (Banister et al. 1997) The approach is similar with GHG emissions, and some examples are already to be found in the literature. Nejadkoorki et al. (2008) adopted a micro-scale approach, whereby data on traffic flows were entered into a traffic modelling programme and combined with detailed GHG emissions coefficients to produce a street level resolution of emissions, which was mapped using geographical information systems (GIS) software. The advantage of this kind of approach, developed by traffic emissions modellers (see for example Namdeo et al. 2002) is that the estimation of total GHG emissions is able to allow for detailed local conditions – such as traffic speed and congestion – and the results can be presented to decision makers in a way that shows the precise location of emissions generation (e.g. major roads).

More relevant to this study is the method of using travel survey data to estimate the total number of passenger kilometres travelled for various transport modes, which can be combined with general mode-specific emissions coefficients to estimate total GHG emissions for a particular urban region, or geographical unit. The advantage of this approach is that the household locations are known, meaning that emissions can be allocated to their household drivers. This approach is particularly suitable to analysis of GHG emissions because, unlike more local pollutants such as particulates, the environmental impact of GHG emissions is global and the specific geographical location of emissions is not as important as the location of the household that uses the polluting mode. This is the approach adopted by (Gavin Alford & Whiteman 2008) in their study of emissions in Melbourne, shown in Figure 2.3.

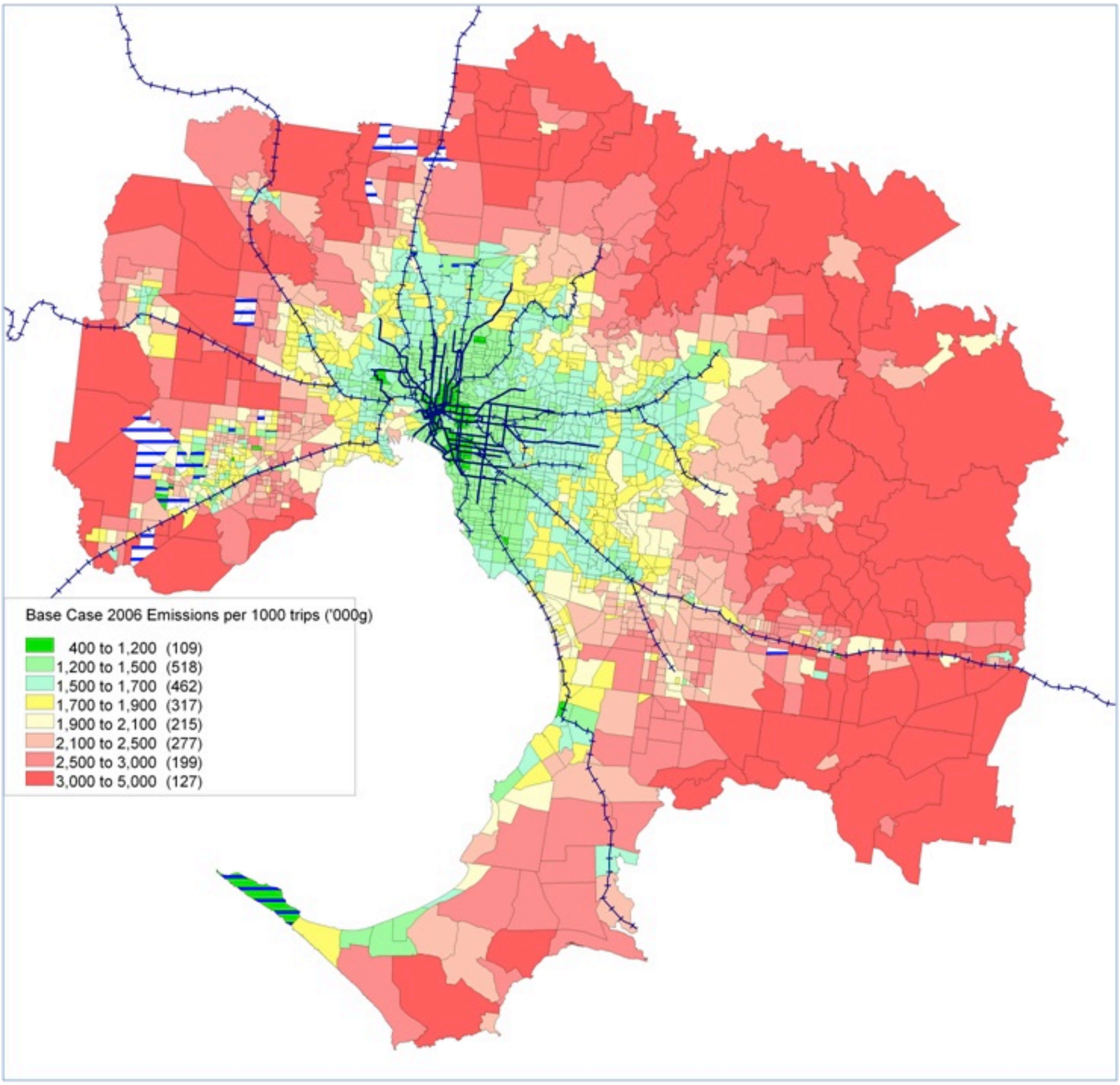


**Figure 2.3 The spatial distribution of transport emissions in Melbourne** ***(Alford and Whiteman 2008)***

The Melbourne study presents its results in terms of emissions per 1000 trips, so-called “travel efficiency”. In this study we will adopt the approach used by (VandeWeghe & Kennedy 2007) in their spatial analysis of emissions in Toronto. Figure 2.4 shows average emissions in Toronto per geographical zone.

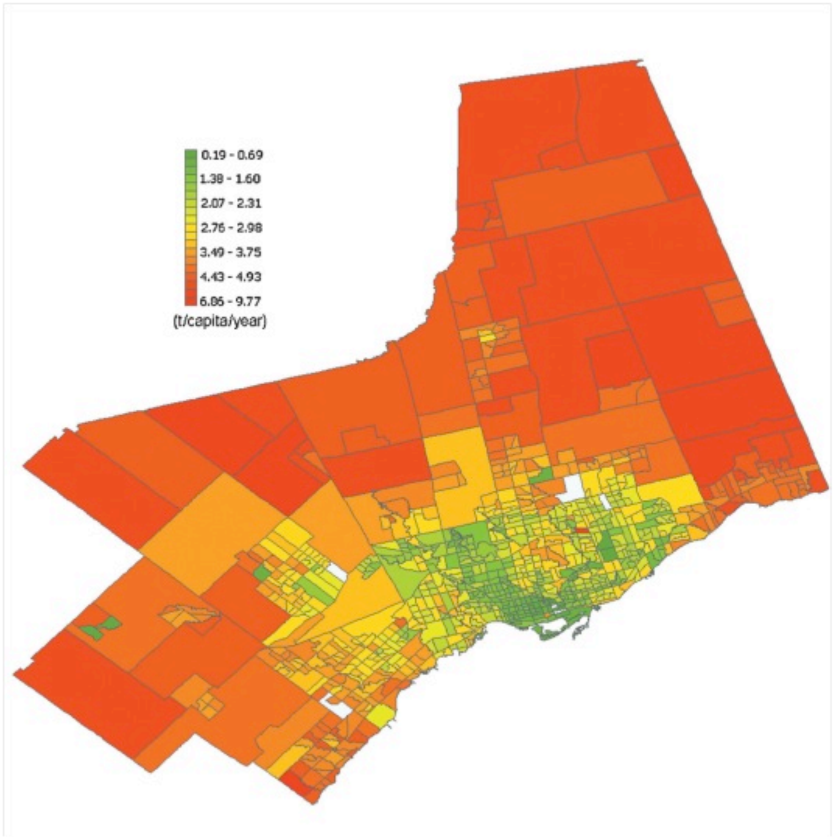


**Figure 2.4 Average per capita transport emission per geographical zone in Toronto** ***(VandeWeghe and Kennedy 2007)***

## 2.4 Spatial analysis and spatial regression

A short note will be made in this review of the debate in the literature regarding the use of aggregation and regression in spatial analysis. Many of the studies of travel behaviour referred to in Section 2.2 used individuals' or households' travel behaviour as the unit of analysis, or dependent variable, in order to establish the causes of variation in travel behaviour statistically. Typically, an individual's travel behaviour is assessed using a travel diary, kept for a period of a week or more (see for example Næss 2006). The data available for the unit of analysis in this study provided individuals' travel records for *one day only*. The resulting extreme variation in the data available for compiling the independent variable meant that some form of aggregation was necessary in order to carry out a meaningful statistical analysis. Support in the literature for this approach is provided by Næss. The following quote is long, but an important reference to the literature for the type of analysis to be undertaken in this study:

> *If we carry out the analysis with the … residential areas as units, most of the relationships become stronger than in the analysis where the units were individual households. In particular, this is true for the associations between travelling distances and the urban planning variables. The households represent a multitude of different value preferences and lifestyles, and the variations in travelling patterns generated by these differences can only to a limited extent be traced back to the variables included in our model. Within the same*

*residential area, for example, members of the local motorist club may have members of the Nature Conservation Society as their nearest neighbours, and a family where each of the spouses drives across the city to a job at the opposite outskirts may live next to another two-income family where one of the spouses has a home office and the partner works in a kindergarten 200 m from the dwelling. If the analysis is carried out with the residential areas as units, these kinds of individual differences will to a large extent be levelled out. What remains of variations between the residential areas may be accounted for by different frame conditions for transport, for example regarding access to various facilities. Such frame conditions may be more in influenced by public policy instruments than variables related to the composition and lifestyle of the individual household. For urban and transport policy planning purposes, it may therefore be more relevant to identify factors in influencing the average travelling pattern of the inhabitants of a residential area than to focus merely on factors in influencing the travel behaviour of individual households.* (Næss et al. 1995)

Using aggregated spatial units presents a problem in spatial analysis known as the ecological fallacy (Freedman 1999). Put simply, the choice of extent or area of each geographical unit of analysis – e.g. postal zone or suburb – will unavoidably mask local variation within that geographical unit, the danger being that the average value for the geographical unit will be taken to represent all points within that area. This is known as the scale aspect of the Modifiable Area Unit Problem (MAUP). A related problem is that changing the borders of the geographical unit of analysis will change the average value – the zonal aspect of the MAUP – meaning that for a specific point on the map two very different average values will be attributed depending on the choice of geographical unit (see Fotheringham & Wong 1991 and Wong and Lee 2005). The exploratory nature of this study means that only a limited account can be taken of this debate in the literature, and the advanced statistical methods suggested in order compensate for the MAUP, but the theme will be revisited in the methodology and discussion sections.

### 2.4.1 Trondheim’s geography

Trondheim is the third largest city in Norway with a population of approximately 170 000 in 2010 (Statistisk sentralbyrå 2012a). Situated in the centre of the country (63°25’47”N 10°23’36”E) it is a major transport and communications hub, with the main north–south national road and rail links running through the town. Trondheim is situated to the south of a large saltwater fjord, and has an extensive, largely uninhabited port area to the north of the town centre.

Figure 2.5 shows the town to have a compact morphology, with communications links running into the town from the south and east. The centre of the town is situated on the half island formed by the curve in the river just before the river enters the fjord. The fairly large settlement area about 8–10 kilometre to the south of the town centre has developed in the last few decades.

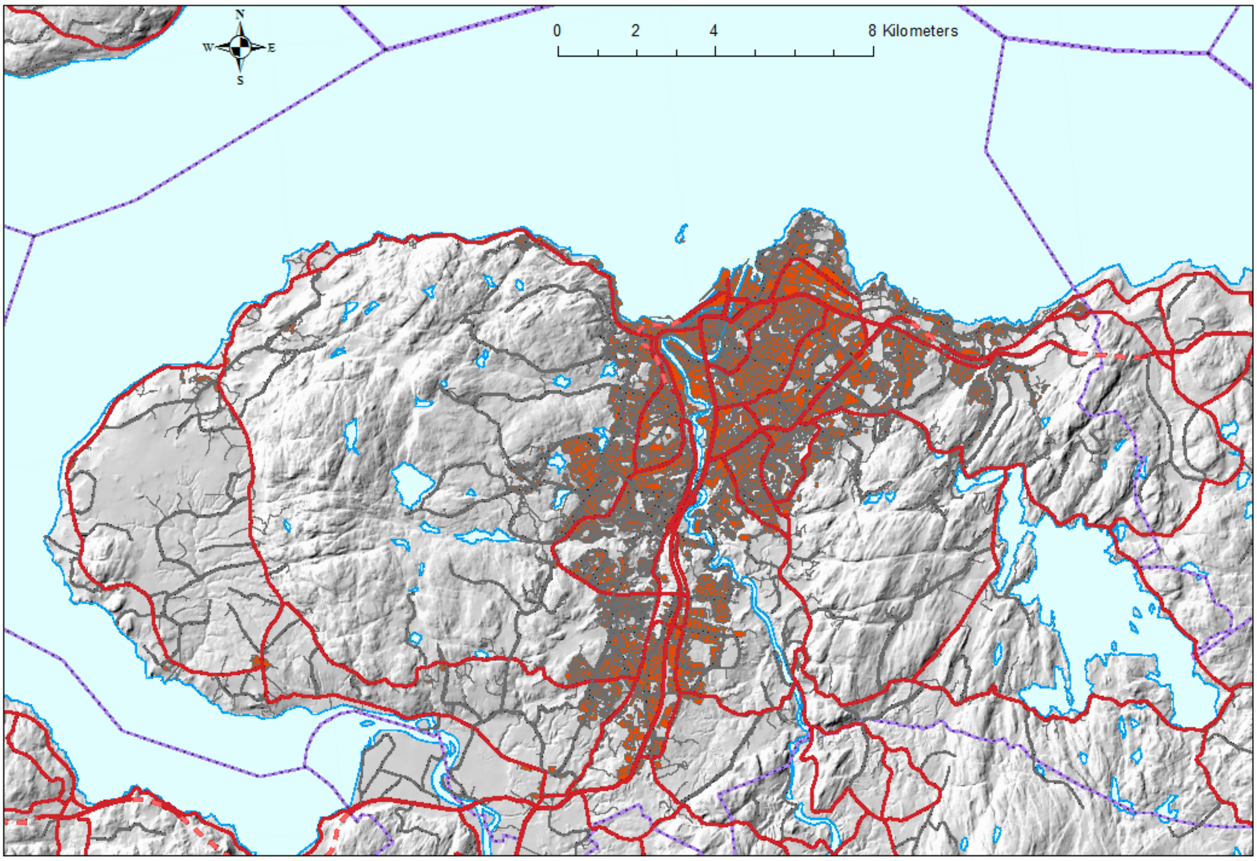


**Figure 2.5 Trondheim: built-areas are shaded orange, administrative borders are shown by the dotted purple line, roads in red and grey**

### 2.4.2 Climate and planning policy in Trondheim

Trondheim's direct GHG emissions were in 2008 around 474 kilotonnes, or approximately 2.8 tonnes per capita: of this total 51 per cent came from transport, 37 per cent from heating and other energy uses, 8 per cent landfill and waste disposal and 4 per cent from land use (Trondheim Kommune 2010b). Emissions from private cars were around 139 kilotonnes, or around 900 kilograms per person (Trondheim Kommune 2008).

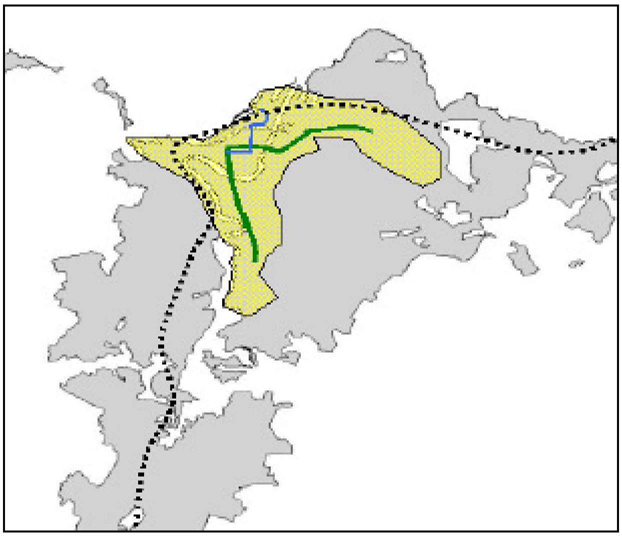
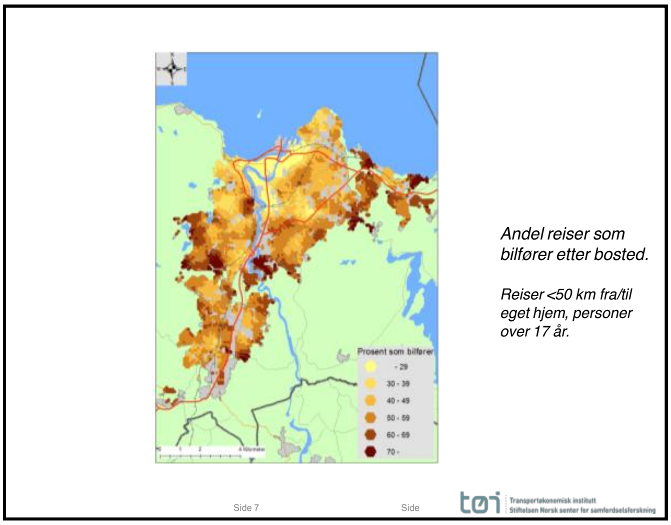


**Figure 2.6 The kollektivbyen in Trondheim, shaded yellow**

Trondheim set ambitious targets to reduce locally generated GHG emissions in its *Climate and Energy Plan* (2010a). The targets are for emissions to be 25 per cent and 70–90 per cent lower than 1991 levels by 2020 and 2025, respectively. Trondheim's population is projected to grow to around 220 000 by 2030 (Trondheimsregionen 2010).

The plan stipulates that 52 kilotonnes of a total 159 kilotonnes of projected cuts in annual GHG emissions by 2020 should come from local transport and land-use policies.  The restriction of private car use is expected to provide 18 kilotonnes of cuts, while 3 kilotonnes are expected to come from improvements to public transport, 1 kilotonnes from the promotion of walking and cycling, 12 kilotonnes from land and parking policy, and a further 18 kilotonnes from the promotion of low-emissions cars and mobility planning (Trondheim Kommune 2010a).

Climate and energy policies are to be implemented in conjunction with regional development policy (the *Interkommunal Arealplan*, IKAP) and the Miljøpakken, a joint strategy between the regional council, the highway agency and the municipality for improved public transport and roads infrastructure (Miljøpakken 2011). The IKAP prescribes that a maximum of 30 per cent of the central area of the town (the *kollektivbyen* shown in Figure 2.6) should be given over to residential buildings, the rationale being that the town centre is the correct location for most commercial and work places (Trondheimsregionen 2010).  The IKAP also states that appropriate consideration should be given to climate, land use and environmental factors when planning for future building developments.   Also of relevance is the provision in the 2008 national climate policy agreement between the main political parties in Norway – *Klimaforliket* – that 80 per cent of new property and commercial developments in Norwegian towns should take place within existing urban areas (Relling 2010).



*Andel reiser som bilfører etter bosted.*

*Reiser <50 km fra/til eget hjem, personer over 17 år.*

**Figure 2.7 Variation in choice of car as choice of travel mode in Trondheim *(Engebretsen 2012)***

A few studies have looked specifically at travel behaviour in Trondheim, and these are useful as a basis for our theoretical understanding and the specification of possible models. Engebretsen (2012) has shown that the choice of transport mode varies spatially in the town. Figure 2.7 shows how the choice of car as travel mode for short trips (under 50 kilometre) to and from home varies in Trondheim. Darker shades indicate a higher percentage of trips by car.  In an earlier study Engebretsen (Engebretsen 2005b) also looked at the relationship between household distance from centre and both mode choice and total travel distance per capita.  Figure 2.8 shows his results for several Norwegian towns.  The figure shows that although total travel distance rises linearly with household distance from centre in Trondheim, the relationship with mode choice is less clear.

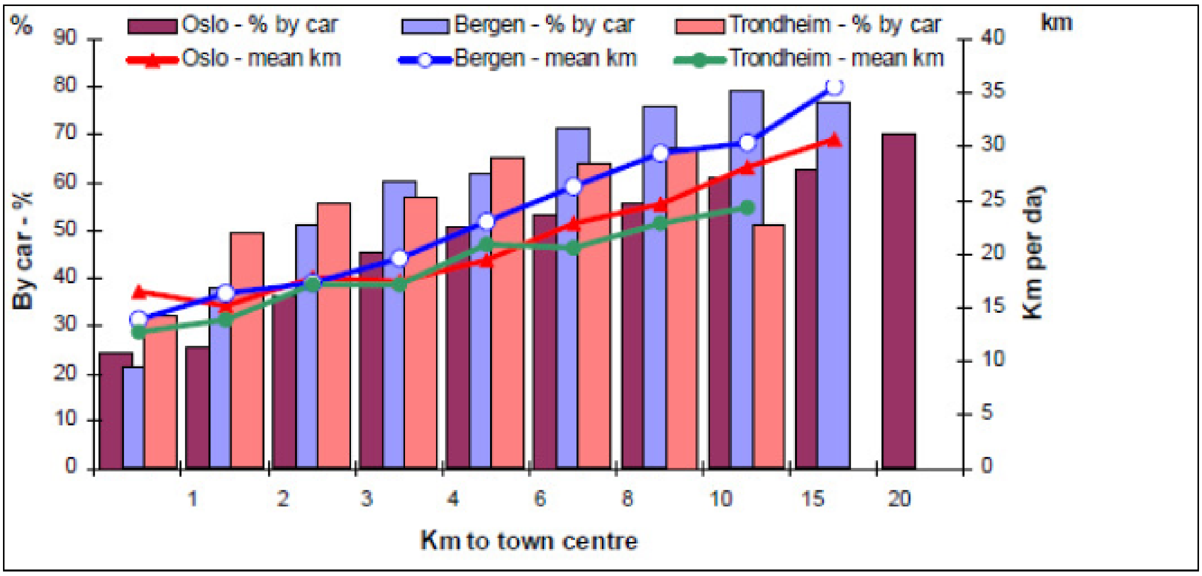


**Figure 2.8 The relationship between residential distance from centre and mode choice and distance travelled in three Norwegian cities *(Engebretsen 2005)***

# 3 Primary Data

The travel survey data used was from the Norwegian *Nasjonale reisevaneundersøkelsen* (national travel survey) or RVU carried out in 2009–10 for the Norwegian Transport Økonomiskinstitutt (TIØ). The survey provides information on private trips taken by a sample of inhabitants aged over 13, including origin of trip, destination, modes used, estimated journey length and motivation for the trip (work, leisure etc.). In a separate file, information is provided on the survey respondent, including the location of their home. However, the Norsk samfunnsvitenskapelig datatjeneste (NSD), which is responsible for data protection issues in Norway, was unwilling to provide the student with the full dataset. Therefore, the student was not provided with full address coordinates for each respondent nor the trip coordinates for trips. Both the residential location and trip patterns of respondents could be identified at a neighbourhood (*grunnkrets*) level.

The Trondheim section of the survey contains responses regarding 23 691 trips taken by 7043 people. Trip lengths are allocated an adjustment weighting, according to criteria such as the day of the week the trip was taken, and the age and gender of the respondent (Vågane et al. 2011, p.6). Taken as a whole, the survey represents travel behaviour for a typical day in Trondheim.

The data was obtained in two IBM SSB (.sav) files: one for trips and one for respondents' personal details. The files are in the format of tables. These were converted into Microsoft Access files for some of the analysis (.mdb). Each row in the table constitutes a separate record of an individual trip (for the trip file) or person (for the respondents file). Each person and trip is allocated a unique identification number: for example person 1254567 carried out trips 1, 2 and 3. By combining these identification numbers, a unique nine-digit number for each trip was obtained (123456701, for example).

Trondheim municipality provided data on the projected demographic growth of Trondheim based on their IKAP plan for the region. The planning consultancy Aplan Viak provided point grids of transport accessibility in Trondheim, which were used to one of the independent variables for the regression analysis. The local public transportation company, AtB, provided data on fuel use and passenger numbers in the Trondheim bus system.

The national statistics authorities were contacted at an early stage in order to obtain socioeconomic and demographic data for explanatory variables for the regression analysis. However, the authorities were unable or unwilling to provide data at the required geographical resolution, so alternative sources were consulted, often the RVU data itself as a parametric source.

All other data sources are cited and listed in the references.

# 4 Methodology and model development

## 4.1 System boundaries

### 4.1.1 Space

The analysis covers emissions arising from travel undertaken by residents living in the geographical area of Trondheim municipality. In addition, a further boundary limit is set on the geographical location of emissions. Emissions resulting from trips made outside the municipality are discounted. The two-part rationale for this is that, firstly, longer trips significantly increase the error term within the functional unit (see Section 5.1) and, secondly, trips made outside the municipality boundaries are theoretically less likely to be influenced by the urban form of the town itself.

### 4.1.2 Scope

The scope of the system is set at direct emissions from transportation. Indirect emissions, such as those arising from the construction of vehicles or the extraction of fuels will not be considered. The emissions targets for Trondheim municipality are set for those emissions that occur within the geographical boundaries of Trondheim. Emissions arising from the following modes of transport were considered: walking, cycling, moped, motorcycling, car taxi, bus and tram. Trips from the following modes were not included: metro, train, aeroplane, boat, snow scooter, tractor and other. This was either because they are not relevant to the direct emissions from the Trondheim urban system or their contribution is negligible.

### 4.1.3 Time

The baseline for the analysis is set at 2010. The travel survey data introduced in Section 3 that form the basis of emissions modelling were collected in 2009-10. Fuel use data for public transportation was not available for that year, so data for 2011 was used instead (see Section 4.3.2). Passenger numbers were available for 2009. Scenario modelling was undertaken for the year 2030. A 20-year time frame was considered long enough for changes in urban form to take place yet short enough to be within the limits of demographic forecasts that could be used as the basis of scenarios.

## 4.2 Three-step model

The modelling for this study comprised three distinct steps, each containing a number of sub-steps. These are summarised in Table 4.1. The detailed methods involved are described in the following Sections, 4.3–5.

Table 4.1 The three-steps of the study model

| | |
|---|---|
| Emissions | The primary aim here was to calculate the functional unit of analysis: average emissions per capita for a defined geographical area. This functional unit was then used as the basis for the independent variable in the regression-modelling step. This step required the establishment of two further model parameters: the geographical unit, or zone, to be used and the vehicle emissions coefficients. |
| Regression | Here the functional unit, emissions per capita per day per geographical unit, was used as the dependant variable in linear regression. The independent, or explanatory, variables were established based on theoretical considerations discussed in the literature review and analysis of the primary data. |
| Scenarios | A baseline scenario was established for the urban development in Trondheim using population and home-building forecasts supplied by Trondheim municipality. Two basic scenarios were established – dispersal and centralisation – and one of the regression models established in step two used to calculate the consequences for GHG emissions in those scenarios. |

## 4.3 Average emissions

Data manipulation for this modelling step was carried out using Microsoft Access and ESRI ArcMap. The estimation of average emissions per capita per geographical unit for use in the subsequent regression analysis was an exploratory process. For reasons of clarity, what is presented here is a simplified version of what in reality was an iterative process, with many of the steps repeated several times as new information and knowledge of statistical methods came to bear.

In order to obtain a functional unit that could be scaled to a population level for use in scenario modelling, the average expressed in the functional unit needed to be the arithmetic mean. The arithmetic mean was calculated by summing the emissions allocated to each geographical unit and dividing by the sum of the number of travelling respondents to the RVU from that geographical unit and a number taken to represent non-travelling inhabitants. The total emissions for each individual were obtained by multiplying the total distance travelled by each mode of transport for each individual by an emissions factor for each mode. The calculations are represented mathematically in Equations 1–3:

$$e = \sum_{s=1}^{46} e_s * p_s \qquad (1)$$

Where $e$ is the total emissions in Trondheim, $p$ is population and $s$ represents the geographical unit, and

$$e_s = \sum_{i=1}^{N_s} e_{i,s} \Big/ N_s + N_{nt,s} \qquad (2)$$

$e_s$ being the average emissions per capita per geographical unit (the functional unit of emissions), $N_s$ being the total number of travelling respondents to the RVU for each geographical unit and $N_{nt,s}$ representing the number of non travellers and

$$e_{i,s} = \sum_{m=1}^{m} d_m * f_m \qquad (3)$$

Where $e_{i,s}$ is the emissions emitted by a particular individual from geographical unit $s$, $d_m$ is the total distance travelled by mode $m$, and $f_m$ is the relevant emissions coefficient per unit distance travelled for the relevant mode of transport.

Relatively unproblematic aspects of the model development were calculation of the length for individual trips and the emissions arising from these. The methods used to obtain the trip lengths will be described first, followed by an explanation of the sources and calculations used to find emissions coefficients for those trips.

### 4.3.1 Trip length calculation

This modelling step was required because, as can be seen in Equation 2, the calculation of emissions relies directly on the availability and accuracy of trip distance figures. Only trips that are assigned a distance can be used in the model and the emissions level is directly proportionate to that trip distance.

The RVU data provided a list of 23 691 trips undertaken by 6151 residents of the greater Trondheim region. In total 15 609 of these trips were taken by 3971 municipal residents within the Trondheim regional area. Around three per cent of these trips were taken for work purposes (excluding commuting) and 76 trips taken using the forms of transport listed in Section 4.1.2 that were excluded from this study. In addition, Trondheim municipal residents undertook 667 trips outside of the municipal area. For reasons discussed in Section 4.1.1 these trips lay outside the system boundaries of the current study and were also excluded.

The original data contained two estimations of trip length: the first was the estimated trip length given by the RVU respondent and the second a corrected version estimated at a later stage. However, in the Trondheim regional survey overall, more than 1000 trips had no respondent trip length and around 22 000 no corrected trip length. In addition, respondents to travel surveys have been shown to show wide variation in the accuracy of their distance estimations (although on an *aggregate* level respondents' estimates have been shown to be a reasonable estimate of distance travelled (Witlox 2007)).

In order to improve the accuracy of the model and to ensure that the largest possible number of trips was included in it, it was decided to model each individual trip using ArcGIS geoprocessing software. This required access to individual trip data, which were not supplied to the student. The student therefore described the required ArcMap routines to the co-supervisor, who carried out the ArcMap routines described in the following paragraphs and returned a list of trip distances, which could be linked back to the data supplied to the student without revealing the geographical location of that trip.

For car trips, the start and finish coordinates of every trip were entered into a road network of the Trondheim. Each coordinate was assigned a trip identification number, meaning that the start and end coordinates were connected and ArcGIS would only solve for the relevant trips, rather than between all possible start and end coordinates. The routes between coordinates along the road network were solved, using time as the impediment assuming that travellers base their route on the quickest rather than shortest option, using the route layer function within the ArcGIS network analysis tool. These were then reinserted into the RVU data in Microsoft Access as a new field. An exemption was made for those trips that returned a length of zero from the network analyst calculation. These were assumed to represent circular trips, whereby the start and end coordinates were the same. Trips within the RVU should not in most cases be recorded in this fashion – a shopping excursion should for example be described by two trips. However it is conceivable either that some respondents made a circular trip simply for pleasure or that in some cases not all stages of a particular journey were recorded by the RVU survey.

The same procedure was carried out for bus trips, using an ArcGIS public transportation network supplied by Asplan Viak, a planning consultancy. The results from this network analysis were returned as a detailed description of the length and time taken between network nodes for each trip, which were also divided between the sections presumed to have been undertaken on foot (from the respondents home to the nearest bus stop, for example, or between bus stops when transferring buses). For each bus trip the total distance actually undertaken on the bus itself was summed and used as the basis for the new estimation of trip length. The rationale for this is that it is only the section of the trip undertaken by bus that creates emissions, and it is this distance that should be inserted into Equation 3. As a final step the corrected length was multiplied by a weighting factor, supplied for each trip in the RVU to ensure representativeness of the data for factors such a day of the week and gender (Transportøkonomisk institutt 2011)

### 4.3.2 Emissions calculation

Equation 3 requires that each trip distance within the system boundaries of the study is multiplied by a relevant and representative GHG emissions coefficient, measured in grammes of carbon dioxide equivalents per passenger kilometre travelled. The transport modes recorded in the RVU data that were used in this study (see Section 4.1.2 for excluded modes) are shown in Table 4.2:

**Table 4.2 Emissions coefficients used**

| Mode | g CO2e/pkm |
|---|---:|
| Foot | 0 |
| Cycle | 0 |
| Moped* | 62 |
| Motorcycle* | 98 |
| Car driver** | 152 |
| Car passenger** | 152 |
| Taxi* | 173 |
| Bus*** | 68 |
| Tram* | 1.2 |

*Sources: * (Toutain et al. 2008), ***(Mäkelä n.d.), ****based on fuel-use data, see Section 4.3.2.2*

The most important vehicle modes for this study are car and bus, which represent 53 and 7 per cent of trips within the system boundaries respectively. In choosing vehicle coefficients for buses and car, consideration was taken of how representative it would be for the technology, driving-cycle and passenger-vehicle ratio within Trondheim. Ideally, coefficients would be based specifically on fuel use and travel data for the Trondheim region. These data were not obtained for cars, but were available for the bus fleet.

#### *4.3.2.1 Emissions coefficient: car*

The emissions coefficient for a car should give the amount of carbon dioxide equivalents emitted in order to transport one person the distance of one kilometre. Note that the term “passenger” in “passenger kilometre” applies to bother drivers and non-drivers of the vehicle in this context.

In the absence of fuel-use data, a review of the literature was carried out and Table 4.3 gives a selection of the coefficients considered.

**Table 4.3 Car emissions coefficients from various sources**

| Source | Fuel/trip type | g $CO_2$e/pkm |
|---|---|---|
| TØI | Gasoline | 107 |
| | Diesel | 82 |
| | Short trip microsimulation | 167 |
| Vestlandsforskning | Short trips petrol | 106,8 |
| | Long trips petrol | 69,4 |
| | Short trips diesel | 94,7 |
| | Long trips diesel | 61,6 |
| VTT | Average | 105 |
| | Urban Diesel | 153 |
| | Urban Petrol | 151 |
| | Urban average | 152 |
| | Highway Diesel | 85 |
| | Highway Petrol | 91 |

*Sources:* (Toutain et al. 2008; Simonsen 2010b; Mäkelä 2011)

The coefficients from the Transport Økonomisk Institutt are for 2004 and are based on various factors specific to Norway, including the age and classification of the vehicle stock and average driving cycle (Toutain et al. 2008), and as such might be considered as representative for Norway as a whole. However, an important consideration that is missing from the calculation of these coefficients is the influence of the urban driving cycle on emissions. In urban conditions the emissions of carbon dioxide is higher per vehicle kilometre and in addition the number of passengers per vehicle is lower. The average number of passengers (including drivers) in Norway is 1.9, but for urban conditions this is reduced to 1.3 (Simonsen 2010b).

The Vestlandsforskning report provides passenger kilometre coefficients for both long trips and short trips, and one can see from Table 4.3 that emissions factors are higher for short trips, as would be expected. However, on closer inspection it can be seen that these estimations are based on the passenger to vehicle ratios only, which in the report are taken to be 1.3 for short journeys and 2 for long journeys. For example, both petrol emissions factors are based on a fleet average emissions coefficient of 138.8 grammes $CO_2e$ per vehicle kilometre. If one divides this figure by 2, one obtains the figure for long journeys, by 1.3 that for short journeys. The differences between the driving patterns in urban and non-urban driving are thus not taken into account.

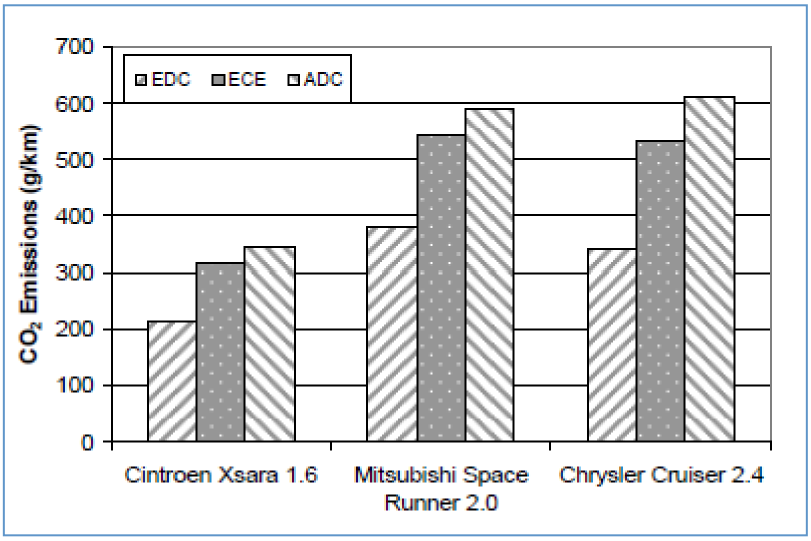


**Figure 4.1 Emissions per vkm for three different vehicles using three different driving cycles (Tzikaris et al. 2006)**

The impact of the driving cycle on emissions per kilometre is important. Figure 4.1 shows emissions for several vehicles using three different driving cycles (Tzikaris et al. 2006). The EDC figures are for cars undergoing the series of starts, accelerations, decelerations and stops taken to represent the typical European driving cycle, while the ECE represents the driving cycle experienced in urban conditions. The final cycle presented, ADC, is specifically modelled for the conditions found in Athens.

A coefficient for urban driving in Norway was not found in the literature. However the VTT Transport Institute provides detailed emissions coefficients for different conditions for the Finnish car fleet. These are based on the LIPASTO model, which in turn is based upon the *Handbook of emission factors for road transport* (HBEFA), the Artemis database of emissions factors for light vehicles and the Copert 4 emissions calculation software from the European Environment Agency (VTT 2009). After consulting the senior traffic scientist at the VTT via email it was decided that the urban driving coefficient would be suitable for use in modelling car emissions in Trondheim (Mäkelä n.d.). This emissions coefficient is substantially higher than the national emissions coefficients provided by TØI but is corroborated by other TØI research, which assessed the emissions per passenger kilometre on short, urban trips taken in the Oslo area, the “Short trips microsimulation” figure in Table 4.3.

It is worth making a note on the impact of diesel engines on carbon emissions. Cars using diesel engines have been promoted in Norway through various tax and other economic incentives. As a result the share of kilometres driven using diesel-powered cars has increased to reach around 50 per cent by 2011 (Statistisk sentralbyrå 2012c). Part of the rationale for this policy is that diesel engines emit less GHG per kilometre travelled. Whilst this is true for highway driving cycles, it is not the case for urban driving cycles, according to the VTT data.

#### 4.3.2.2 Emissions coefficient: bus

Table 4.4 shows GHG emissions coefficients for buses in Norway for various fuel types and regions.

**Table 4.4 Emission coefficients for Norwegian buses**

| Bus | $CO_2e$/pkm |
|---|---:|
| Norway 2005 | 62 |
| Town bus Oslo 2009 | 94 |
| Express bus Norway 2007 | 52 |

*Source: (Simonsen 2010a)*

The variation is considerable. The passenger kilometre coefficient is particularly sensitive to the ratio of passengers to vehicles. In an earlier study (Loveland 2011) the student used the Norway average, which is the coefficient provided by TØI (Norway 2005 in Table 4.4). However, the local bus operator, AtB, was able to provide fuel-use data for the majority of bus routes within Trondheim, and this was used in conjunction with data from the RVU survey to produce a coefficient specifically modelled on parameters for Trondheim.

The formula for emissions per passenger kilometre is shown in Equation 4.

$$\frac{g}{pkm} = \frac{total\ emissions\ from\ bus\ fleet}{total\ passenger\ kilometres\ from\ bus\ fleet} = \frac{total\ emissions\ from\ bus\ fleet}{total\ number\ of\ trips * average\ trip\ lenth} \qquad (4)$$

Table 4.5 shows fuel-use data for numbered bus routes in Trondheim in 2011, together with emissions factors per unit of fuel (DEFRA 2010) . The fuel-use data was obtained from emails from AtB staff. Further documentation was not available. Fuel use data was not available for 2010, so does not match the RVU survey exactly.

**Table 4.5 Fuel use data for bus routes in Trondheim (*Source: AtB*)**

| Bus route | Natural gas (sm3) | Biodiesel (litre) | Diesel (litre) |
|---|---:|---:|---:|
| 46,146, 154 | 226846 | 0 | 0 |
| 10,11,20,36,52,55,60,66,67,80,93,94, 95,97,104,105,106,107,109,119,136,155 | 489263 | 0 | 0 |
| 4,5,6,7,8,9,777 | 1287100 | 50500 | 672000 |
| **CO2e per unit fuel** | 2027 | 1585 | 2672 |
| **g CO2e** | 4060504643 | 80042500 | 1795584000 |

A different perspective could be obtained by looking at the indirect emissions or possible emissions savings in the case of biofuels embedded in each fuel type, but indirect emissions lie outside the system boundaries of this study. The row sum in Table 4.5 was taken as the total emissions from those bus routes in 2011 and was used as the nominator in Equation 4.

The average length of a trip in Trondheim was taken as the average trip length for bus trips in the RVU dataset: 6.9 kilometres. The number of passenger trips for each bus route was obtained from AtB (see Appendix I). This number was reduced by 10 per cent as an estimation of the influence of trips undertaken using more than one bus, based on conversations with the students co-supervisor. Multiplied together these two figures provided the number of passenger kilometres travelled in Trondheim in one year. The resulting emissions coefficient, calculated using the formula shown in Equation 4 is shown in Table 4.2.

### 4.3.3 Establishing the geographical unit

#### *4.3.3.1 Guiding principles: random error and the ecological fallacy*

The establishment of the geographical unit was guided by two main principles. Firstly, there was the need for a statistically robust sample for the function unit (average emissions per geographical unit) that reduced the effect of random variation. Although it is possible to carry out statistical regression of travel behaviour and emissions on individuals, the amount of random error is very large. The problem of random variation is particularly acute when using RVU data. Studies such as Næss's that have used statistic regression on individuals travel behaviour have typically had access to a trip diary, showing the respondent's travel behaviour over an extended time period. In contrast, the RVU respondents provided information regarding their travel behaviour for one day only, making each individuals response a poor guide of their own typical travel behaviour, and an even worse guide to the travel behaviour of the typical resident in their geographical location. There is a link between the size of the geographical unit and sample size – a larger geographical area is likely to contain a greater number of residents contacted by the RVU than a smaller area.

Secondly, the geographical unit needed to be of a size and extent that would prove useful from a planning and decision-making point of view. Although, very large geographical units are more likely to provide a large sample on which to base the functional unit, they are also more likely to mask real variation and increase the extent of the so called ecological fallacy. The ecological fallacy occurs when average values for a geographical area taken to represent all the individual data points within that area. The ecological fallacy is linked to the modifiable area unit problem, introduced in Section 2.

To summarise, the choice of geographical unit is based on a trade-off between the competing statistical demands of error reduction on the one hand, and reducing the extent of the ecological fallacy within the system model on the other.

#### 4.3.3.2 Aggregation options

Various options were considered for the aggregation of individual RVU respondents into geographical units (David W S Wong & J. Lee 2005). However, due to difficulty obtaining clear guidance on the statistical methods involved in the aforementioned aggregation techniques and a lack of clarity from the NSD authorities on whether the student would gain access to residential address coordinates, it was decided to base the geographical unit of analysis on the *grunnkrets* division of the Trondheim municipal area.

#### 4.3.3.3 Grunnkrets and delområde

The *grunnkrets* is the basic geographical unit used by the Norwegian authorities to delineate land for planning and statistical purposes coming at the bottom of a range from *fylke* (largest), *kommune* (municipality), *bydel*, *delområde* to *grunnkrets*. Norway itself is divided into approximately 14 000 *grunnkretser* (Norwegian Mapping Authority 2012). Each *grunnkrets* is given an eight-digit code. Trondheim municipality is divided into 432 *grunnkretser*, shown in Figure 4.2.

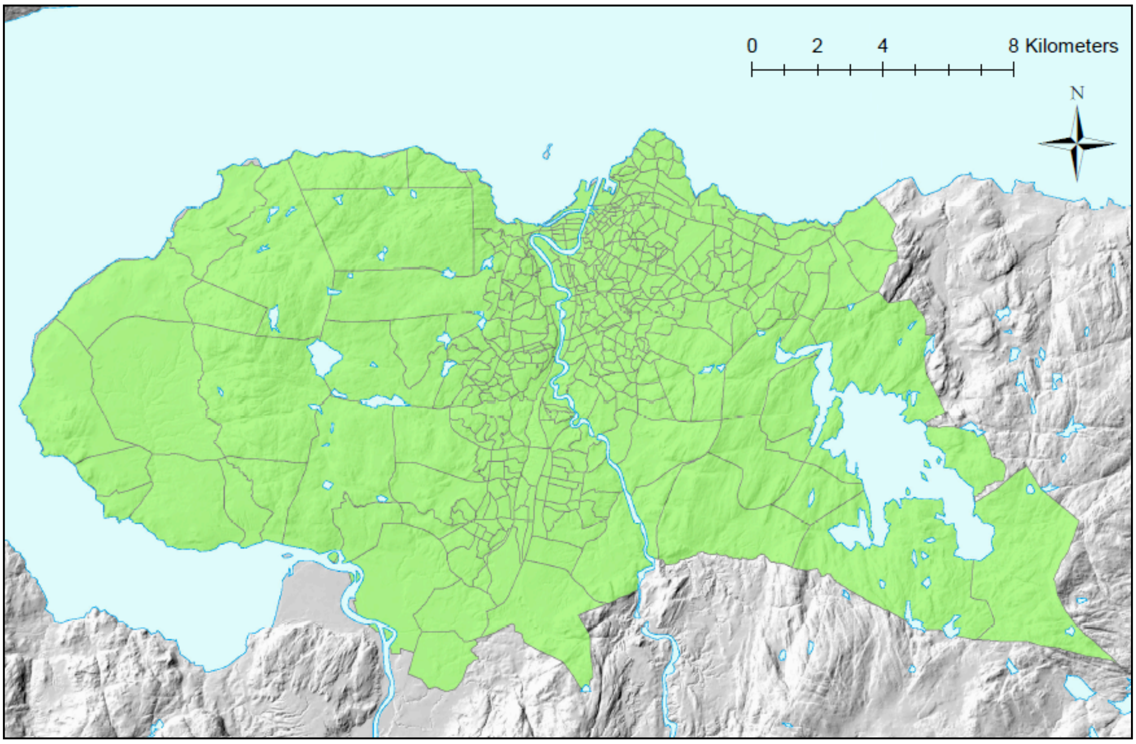


**Figure 4.2 Trondheim municipality (shaded green) divided into grunnkrets**

The advantage of using *grunnkrets* as the basic unit of analysis was twofold: firstly, *grunnkrets* represents a contiguous geographical area that is already used by the planning authorities to represent a relatively homogeneous social and geographic entity, and, secondly, the data provided to the student did not contain individual address coordinates, making other aggregation methods impractical. The disadvantage of using the *grunnkrets* is that in the majority of cases the RVU returned very small numbers of respondents per *grunnkrets*. Figure 4.3 shows the distribution of number of respondents per *grunnkrets* in the RVU dataset. The average sample size for the *grunnkrets* was just 13, well below the 30 required to apply standard statistical techniques such as error estimation using the central limit theorem, for example. Many *grunnkrets* returned zero respondents.

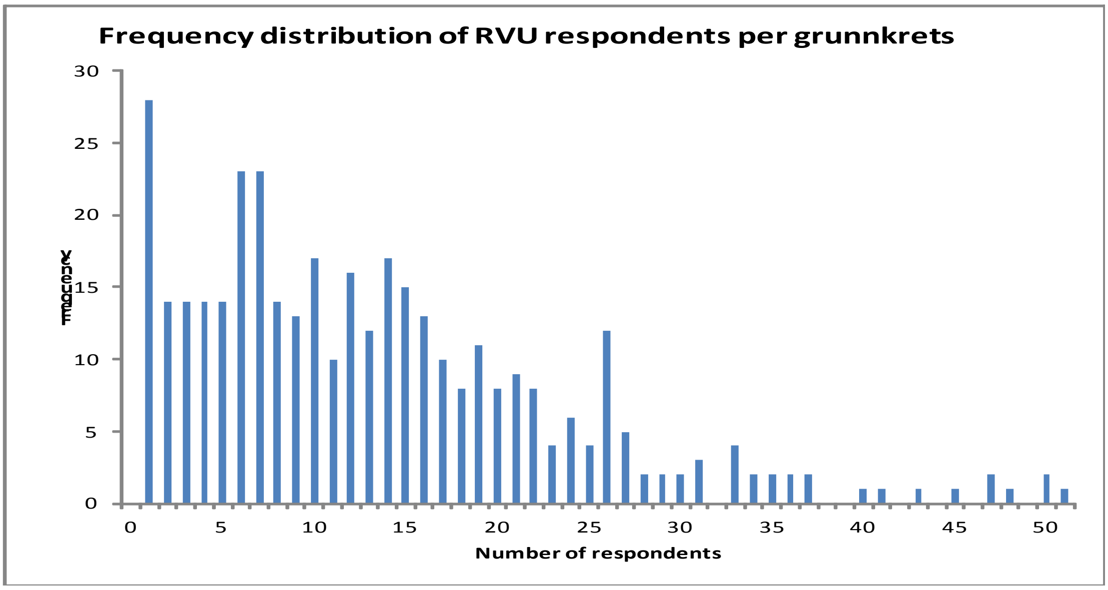


Figure 4.3 Histogram of responses per grunnkrets

Trondheim can also be divided into 24 *delområder*, represented by the sixth and seventh digit of the *grunnkrets* code. The student used this *delområde* unit in an earlier study to establish the relationship between residential distance from centre and average emissions. However, the large size of the *delområde* limits its practicality from a planning perspective and increases the likelihood of the ecological fallacy occurring.

#### 4.3.3.4 Sone

Various techniques were considered for aggregating the *grunnkrets* into larger geographical units that contained a large enough sample size to be statistically meaningful ( Wong & Lee 2005). For example *grunnkretser* could be aggregated on an iterative basis whereby those containing a relatively large sample could be joined to surrounding units until a predetermined sample size is reached. However, there are inherent problems with this approach. For example, should two *grunnkrets* separated by a large barrier such as a river or major road be aggregated? This might make sense statistically in order to create a large enough sample of respondents but not from the point of view of spatial analysis. In personal communication with members of the geography department at NTNU it became known that the aggregation of *grunnkrets* into spatially meaningful units had been carried out in the recent past for another study (Brattbakk et al. 2000). It was decided to adopt this system for the spatial division of Trondheim. The benefits of dividing Trondheim into the system of *soner* included:

- *Soner* provide a finer resolution than *delområder*, but nevertheless correspond with pre-existing planning delineations of the town;
- The *soner* have less variation in population size (between approximately 1700 and 7000 inhabitants) than either delområder or grunnkretser;
- *Sone*r delineations follow school districts to a large extent, and can be seen as representing specific communities with specific identities within the town;
- As a rule *soner* borders take into account natural physical barriers such as main roads and rivers;
- *Soner* are generally characterised by a relatively homogenous built-environment in terms of building type etc. *(Brattbakk et al. 2000, p.49)*

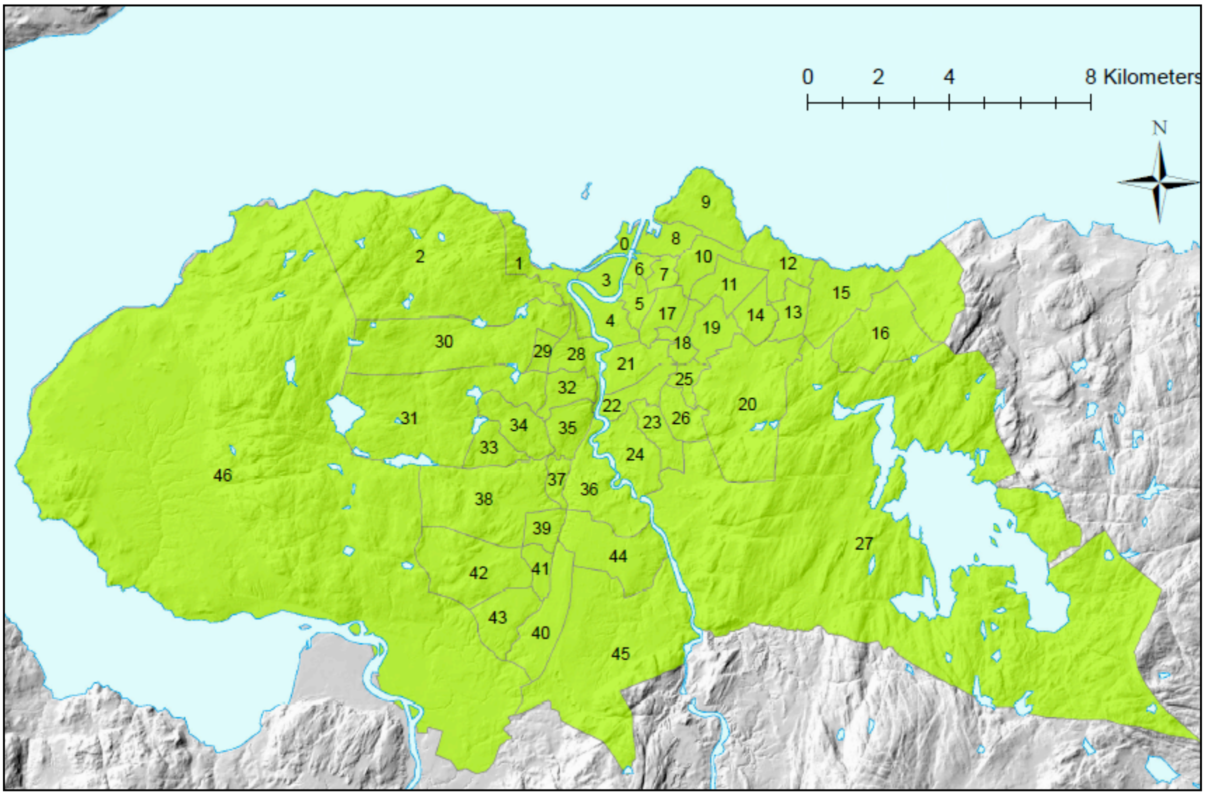


Figure 4.4 Trondheim municipality divided into sone

The division of Trondheim into 46 *soner* is shown in Figure 4.4. *Sone* 0 represents an unpopulated area in the port district. A table showing *sone* population, area and residential area can be found in Appendix II.

### 4.3.4 Combining trip modelling, emissions coefficients and geographical units

Once the trips relevant to the modelled system had been established using Access routines, the emissions coefficients obtained or calculated, and the geographical unit established, it was possible to use Equation 3 to calculate average emissions per day per traveller per *sone,* which would then form the basis of the functional unit used as the dependant variable in the regression modelling step.

### 4.3.5 Establishing the functional unit of emissions

The functional unit of emissions in this study is average emissions per capita per day per *sone*. This was obtained by dividing the travellers emissions described in Section 4.3.4 by the number of respondents in the *sone* sample ($N_s$) plus an allowance for people not travelling on that particular day ($N_{s,nt}$). The number of people not traveling was assumed to be represented by respondents present in the *personfil* of the RVU but not present in the *resisefil* – i.e. those who responded to the survey but did not register trips. On examining the number of non-travelling respondents by *sone* it was established that this varied substantially as a percentage of total respondents. As a theoretical basis for this variation, and having consulted the literature, which suggested that respondents reporting no trips are not always reliable (Madre et al. 2007), it was decided to use the Trondheim average for non-travelling respondents for each case – 14 per cent. This is an assumption and will be discussed in Section 6.

## 4.4 Regression modelling

### 4.4.1 Variables

The regression step of the model involved the testing of the dependant variable (i.e. the functional unit of emissions or average emissions per capita per day per *sone*, in this section referred to as the dependent variable) against a number of urban-form, socioeconomic and demographic independent variables using linear regression. These variables were chosen after consultation of the literature outlined in Section 2. However, due to factors outside the control of the student (see Section 3), the preferred data-source for each variable was not always available. Table 4.6 shows the variables identified in Section 2, the preferred source for each variable and the eventual method used to find this variable, if possible. A more detailed account of the establishment of values for each independent variable follows in Section 4.4.1.1 to 4.4.1.7.

Table 4.6 Variables considered and their sources

| **Variable** | **Preferred Source** | **Eventual solution** |
|---|---|---|
| **Household distance from centre** | ArgGIS network analysis | ArgGIS network analysis |
| **Accessibility by public transport** | Aplan Viak study | Aplan Viak study |
| **Population density** | Trondheim municipality | Trondheim municipality |
| **Parking availability** | Trondheim municipality | Data does not currently exist |
| **Income level** | Statistisk sentral byrå | RVU parametric variable |
| **Educational level** | Statistisk sentral byrå | Data not made available |
| **Workforce participation** | Statistisk sentral byrå | Data not made available |
| **Car ownership** | Statistisk sentral byrå | RVU parametric variable |
| **Age** | Trondheim municipality | Trondheim municipality |
| **Retail density** | Commercial register | Commercial register |

#### *4.4.1.1 Distance to centre*

The variable distance to centre represents the average distance along the road network to a predetermined point in Trondheim city centre (63°25’55”N 10°23’31”E). The link between distance from city centre and distance travelled by residents is clearly established in the literature (see Section 2). For each *sone* this is based on the average of the distance from the centre point of each *grunnkrets* within that *sone* to the town centre. The centre point of each *grunnkrets* in this case is calculated as the centre in relation to the buildings found in each *grunnkrets*. It is therefore more closely linked to inhabited areas or settlement than a centre point based merely on the dimensions of the *grunnkrets* polygon. A map showing *grunnkrets* and their respective central points is found in Appendix III. Network distances were calculated using the route finder function in the network analyst tool in ArcGIS.

#### *4.4.1.2 Retail density*

Based on the literature outlined in Section 2, a variable measuring the density of retail establishments per square kilometre in each *soner* was also introduced to the model, using a registry of commercial properties in Trondheim. Only retail establishments selling everyday goods and groceries were included. On inspection of the scatterplot of retail density to emissions it was decided to use the natural log of the actual density because this resulted in a more linear relationship.

#### 4.4.1.3 Accessibility by public transport

The public transport system in Trondheim is mainly a bus-based system. As buses were found to have a much lower emissions coefficient than cars in Section 4.3.2, there were strong theoretical reasons for assuming that accessibility by public transport would effect average emission in each *sone.* This variable was calculated using pre-existing maps of Trondheim supplied by the planning consultancy firm, Asplan Viak. Each map comprised point grids of the Trondheim municipal area (see Appendix IV). At each point on the grid, the average travel time from that point to every other point in the grid is given. A high travel time represents relatively low accessibility. These point grids were available for travel both by car and by public transport. Using ArcGIS, an indicator of the relative ease of travel by public transport at each grid point was obtained by finding the ratio of travel time by public transport to travel time by car. A high value shows means that it relatively more time costly for a traveller to take the public transport option compared to grid points where the ratio is lower (the minimum ratio for all grid points is about 1.5). The average value for each *sone* was used as the independent variable for accessibility of the area by public transport.

#### 4.4.1.4 Population Density

Some link was found between neighbourhood density and travel behaviour in the literature (See Section 2). Population density is a function of both the population in the geographic zone under analysis and the parameters used to establish the area of that zone. A cursory view of a satellite map of Trondheim shows that only a small fraction of the total municipal area is settled. Theoretically, a higher population density in a person's immediate environment reduces their need to travel large distances in order to visit friends or family, for example. It was therefore decided that a better measure of area than the entire geographic extent of each *sone* would be the area around human settlements, or populated area. Publicly available map layers showing built-up areas seemed fairly inconsistent. For example, in some neighbourhoods the space between blocks of flats was considered to be built-up while in other areas this was not the case. In order to achieve consistency a 50 metre circular polygon was created around each residential building in Trondheim using ArcMap, using the Norwegian definition of a settlement (*tettstet*) as a guide (Statistisk sentralbyrå 2012b). These polygons were merged according to *sone*, and the resulting area used as the denominator in the calculation of population density. A map showing the *sone* areas using the method described above can be found in Appendix V.

#### 4.4.1.5 Income level

The literature shows some link between income and travel behaviour. In the absence of complete data from the Statistisk Sentral Byrå, it was necessary to obtain an indicator of the variation in income level from secondary sources, in this case the RVU itself. Respondents to the RVU were asked to indicate their household income according to an ordinal scale. The income bands were in intervals of 100 000 NOK, with the uppermost band being open-ended at 700 000 plus. Each respondent who had supplied an income figure was assigned a value at the midpoint of the relevant band (i.e. 550 000 for the income band 500 000–600 000 NOK) and the average income for each *sone* obtained. There are obvious shortcomings to this method. However, the geographical distribution of income corresponded well with the earlier study of socioeconomic variation in Trondheim by Brattbakk et al. (2000).

#### 4.4.1.6 Car ownership

Car ownership has been shown to be a strong predictor of travel behaviour in the literature. Again, the Statistisk Sentral Byrå did not make complete data on car ownership levels available and the RVU data were used as a secondary source. Respondents to the RVU were asked if they had access to a car. The proportion of positive respondents was found by *sone*.

#### 4.4.1.7 Age

The inclusion of a demographic variable based around age was based on the theoretical assumption that travel behaviour changes by age. Finding the average trip emissions by age for Trondheim could test the veracity of this assumption. This is displayed in Figure 4.5.

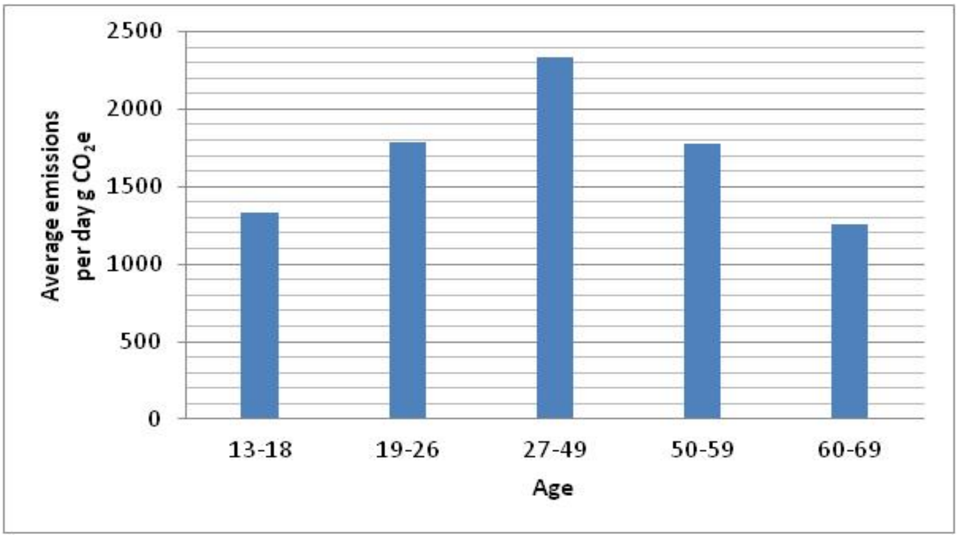


**Figure 4.5 Emissions per day by age group in Trondheim**

The data shows that travel behaviour increases with age, plateaus during middle age, and then reduces thereafter. The data for older travellers could not be considered reliable as they are based on a small number of respondents. The use of average age was discarded as it showed very little variation by *sone*. The percentage of population under sixteen years of age did vary however, and it was decided to use this as a demographic variable, in part because the literature showed a link between family structure and household travel behaviour. The inclusion of this variable was only decided upon during the modelling stage, but leads to some interesting discussion on the assumptions of causality within regression analyses and urban systems in general, see Section 6.

### 4.4.1.8 Summary of independent variables

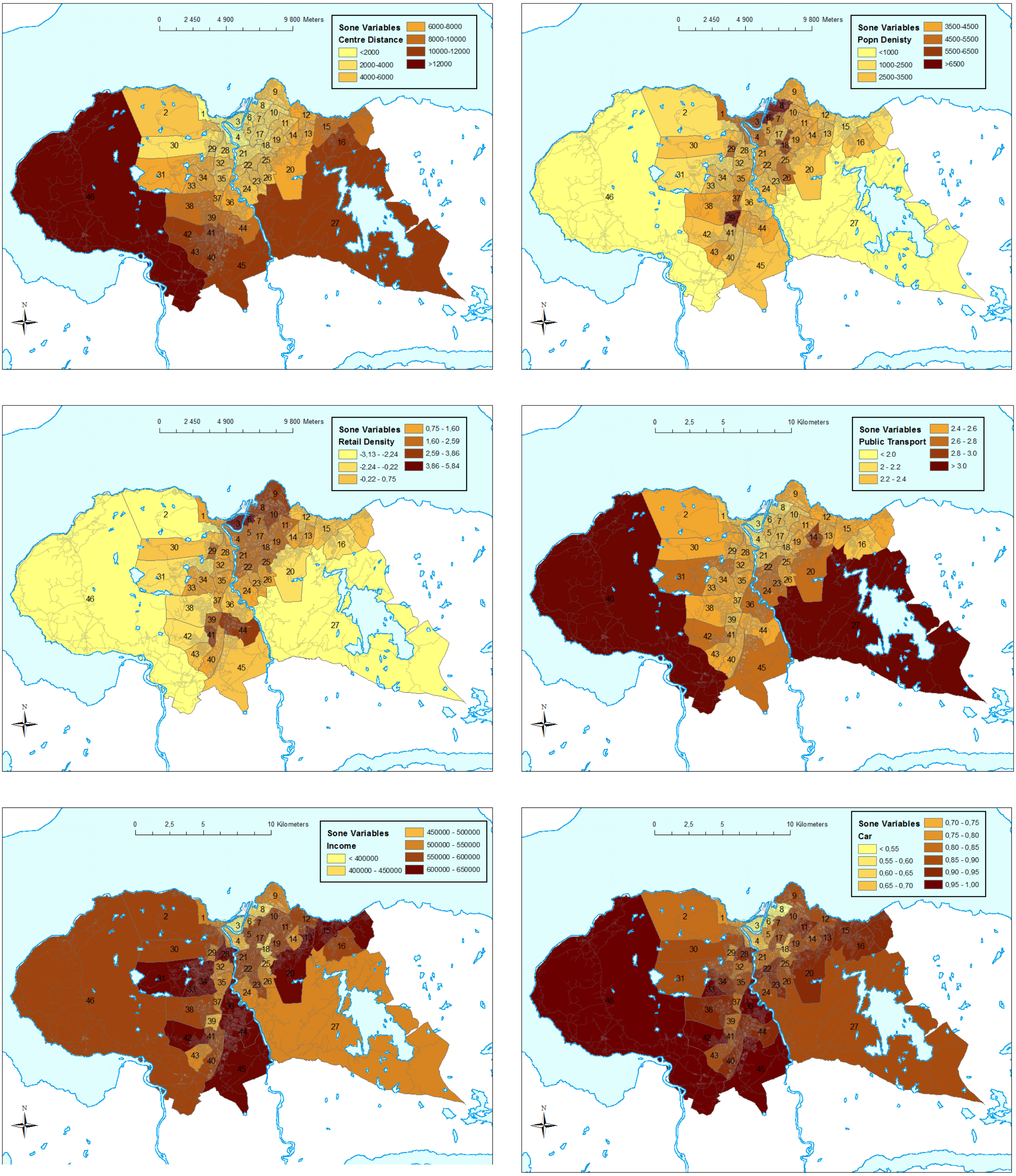
Table 4.7 shows the independent variables used in the following regression analysis.

**Table 4.7 Independent variables**

| Sone | Centre distance | Popn density | Retail density | Public transport | Income | Car | Under 16 |
|---|---|---|---|---|---|---|---|
| 1 | 1782 | 5220 | 1,58 |  | 531395 | 0,76 | 0,12 |
| 2 | 4423 | 2308 | -2,24 | 2,60 | 593636 | 0,81 | 0,23 |
| 3 | 500 | 6045 | 5,84 | 1,87 | 394595 | 0,36 | 0,05 |
| 4 | 1719 | 5165 | 2,20 | 2,04 | 460577 | 0,66 | 0,12 |
| 5 | 2107 | 4121 | 2,40 | 2,28 | 570619 | 0,79 | 0,18 |
| 6 | 1713 | 10935 | 4,82 | 2,04 | 494186 | 0,57 | 0,09 |
| 7 | 2476 | 4845 | 2,34 | 2,29 | 562500 | 0,85 | 0,18 |
| 8 | 2653 | 9151 | 3,28 | 2,07 | 432677 | 0,50 | 0,10 |
| 9 | 4325 | 4010 | 2,88 | 2,59 | 549237 | 0,86 | 0,19 |
| 10 | 3677 | 3550 | 3,46 | 2,23 | 569811 | 0,88 | 0,19 |
| 11 | 4434 | 3994 | 2,59 | 2,42 | 592222 | 0,91 | 0,22 |
| 12 | 6656 | 2990 | 0,53 | 2,51 | 597191 | 0,88 | 0,25 |
| 13 | 7301 | 3456 | 0,85 | 2,52 | 627273 | 0,92 | 0,26 |
| 14 | 6216 | 4025 | 1,09 | 2,88 | 533721 | 0,85 | 0,19 |
| 15 | 8812 | 2306 | 0,26 | 2,46 | 612037 | 0,91 | 0,25 |
| 16 | 10221 | 2795 | -1,48 | 2,36 | 569403 | 0,90 | 0,31 |
| 17 | 2851 | 3470 | 1,92 | 2,34 | 581429 | 0,88 | 0,21 |
| 18 | 3770 | 5519 | 2,28 | 2,38 | 427108 | 0,68 | 0,15 |
| 19 | 5106 | 3608 | 1,82 | 2,57 | 561111 | 0,86 | 0,23 |
| 20 | 6382 | 2725 | -0,22 | 2,67 | 609864 | 0,93 | 0,20 |
| 21 | 3054 | 3797 | 2,10 | 2,37 | 558772 | 0,82 | 0,19 |
| 22 | 4131 | 3592 | 2,07 | 2,63 | 580159 | 0,90 | 0,20 |
| 23 | 5455 | 3030 | 1,06 | 2,75 | 586709 | 0,95 | 0,23 |
| 24 | 5521 | 2861 | 1,14 | 2,67 | 512000 | 0,89 | 0,19 |
| 25 | 4832 | 4286 | 2,22 | 2,56 | 496667 | 0,85 | 0,16 |
| 26 | 5603 | 5016 | 1,03 | 2,59 | 546471 | 0,87 | 0,21 |
| 27 | 11796 | 651 | -3,13 | 4,05 | 513889 | 0,88 | 0,27 |
| 28 | 3364 | 2571 | 1,00 | 2,52 | 615854 | 0,90 | 0,22 |
| 29 | 3867 | 4849 | 2,24 | 2,37 | 515263 | 0,78 | 0,19 |
| 30 | 3520 | 3386 | 0,49 | 2,45 | 584524 | 0,86 | 0,21 |
| 31 | 6243 | 2006 | -0,63 | 2,64 | 621000 | 0,87 | 0,26 |
| 32 | 5151 | 2880 | 1,28 | 2,59 | 540278 | 0,80 | 0,22 |
| 33 | 7384 | 3103 | 1,01 | 2,45 | 650000 | 0,97 | 0,29 |
| 34 | 6712 | 3153 | 1,17 | 2,47 | 613492 | 0,93 | 0,26 |
| 35 | 5972 | 3881 | 1,60 | 2,45 | 519903 | 0,85 | 0,20 |
| 36 | 7243 | 3190 | 0,41 | 2,67 | 611194 | 0,96 | 0,26 |
| 37 | 7214 | 4505 | 0,99 | 2,32 | 537179 | 0,83 | 0,21 |
| 38 | 8943 | 4259 | -0,35 | 2,51 | 593548 | 0,91 | 0,24 |
| 39 | 9707 | 7044 | 2,32 | 2,38 | 465789 | 0,81 | 0,20 |
| 40 | 10247 | 2722 | 1,16 | 2,58 | 592857 | 0,92 | 0,21 |
| 41 | 10030 | 3174 | 3,86 | 2,56 | 587931 | 0,88 | 0,22 |
| 42 | 11223 | 2566 | -0,93 | 2,67 | 642771 | 0,97 | 0,24 |
| 43 | 11113 | 4463 | 0,75 | 2,48 | 543878 | 0,90 | 0,25 |
| 44 | 8991 | 4224 | 3,08 | 2,44 | 622115 | 0,91 | 0,25 |
| 45 | 10507 | 2537 | 0,06 | 2,69 | 628495 | 0,98 | 0,26 |
| 46 | 17291 | 684 | -2,70 | 4,06 | 592708 | 0,97 | 0,25 |

*Units: Centre distance, metres; Population density, inhabitants per square kilometre inhabited area; Retail density, natural log of retail establishments per square kilometre; Public Transport, average point-to-point travel distance public transport normalised by point-to-point distance by car; Income, household income in NOK; Car, proportion of RVU respondents with access to car; Under 16, proportion of sone inhabitants under the age of 16.*

Figure 4.6 on the next page shows the spatial distribution of each variable by *sone*.



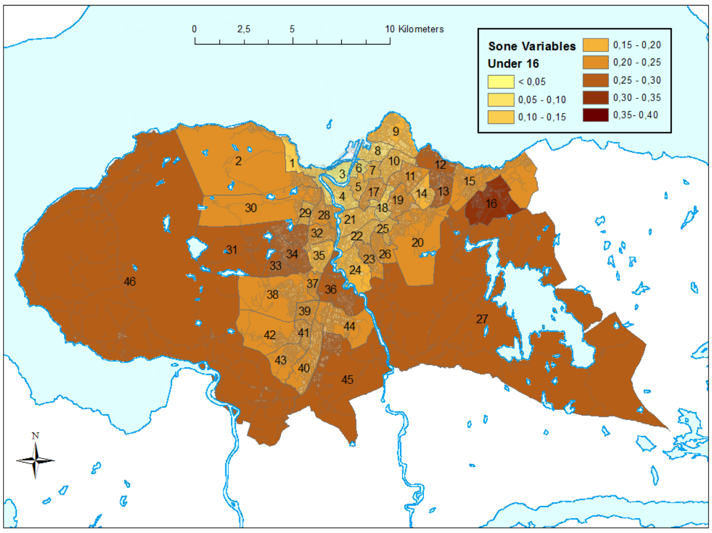


**Figure 4.6 Spatial distribution of independent variables (units below)**

***Centre distance****: metres*

***Population density****: inhabitants per square kilometre inhabited area;*

***Retail density****: natural log of retail establishments per square kilometre;*

***Public Transport:*** *average point-to-point travel distance public transport normalised by point-to-point distance by car;*

***Income****: household income in NOK;*

***Car****: proportion of RVU respondents with access to car;*

***Under 16****: proportion of sone inhabitants under the age of 16.*

### 4.4.2 Linear regression

The linear regression analysis was carried out using two different statistical software packages, IBM SPSS and ArGIS Spatial Statistics. The advantage of using both was that each had slightly different diagnostic capabilities, which enabled cross checking of assumptions. For example, SPSS uses the Shapiro-Wilk and Kolmogorov-Smirnov test of distribution normality whereas ArcGIS uses the Jarque-Bera test. In the case of normality in particular, it is useful to have access to several different diagnostic tests, because no test is perfect and are easily influenced by the presence of outliers (Field 2005). SPSS has more functionality in the linear modelling stage: one is able to enter variables hierarchically, assign weighting values, and carry out stepwise regression whereby variables are added or removed from a model according to predetermined p-values. However, a new extension to the ArcGIS spatial statistics toolbox, Exploratory Regression, enables one to carry out all possible combinations of variables simultaneously. This proved a very powerful exploratory tool, with the advantage over stepwise regression that the effect of combining different variables could be viewed transparently in a full diagnostic report, and was not left to arbitrarily predetermined p-values. A further advantage of the ArcGIS software was that residuals for each regression could be mapped, enabling the spatial analysis of each regression model. An additional option was to carry out Geographically Weighted Regression, whereby the coefficients of each independent variable are allowed to vary spatially.

#### *4.4.2.1 Assessment of the bivariate correlation of the variables*

The independent and dependent variables were plotted against each other in scatterplot diagrams and examined for patterns and relationships. The Pearson's product-moment correlation coefficient was also obtained for all bivariate combination of variables. The results of correlation assessment are presented in Section 5.2.1.

#### *4.4.2.2 Hierarchical regression*

The order in which variables are entered into a regression analysis can affect the resulting model parameters (Field 2005). Independent variables that have been demonstrated as relevant by earlier work or that have strong theoretical basis for inclusion should be entered into the model first. Accordingly, the centre distance variable, which has a strong theoretical basis and had been found by the student to affect the average emissions of larger geographical units, was entered into the model first. Population density and access to public transport were also considered to be strong candidates, the former due to evidence in the literature and the latter because of the model parameters: an area with better access to the bus system in Trondheim should in theory produce lower emissions on average. Hierarchical regression was therefore carried out in SPSS, entering centre distance first followed by the other two strong candidates.

#### *4.4.2.3 Exploratory regression in ArcGIS*

The exploratory regression function in ArcGIS was used to model the effect of further variables. The exploratory regression function allows for all combinations of variables to be tested simultaneously, in separate regression analyses. The advantage with this approach is that potentially significant variable that have been overlooked in the researcher may come to fore. Setting threshold p-value for variable significance too low can eliminate a potentially very useful explanatory variable (Walpole et al. 2012). Therefore, exploratory regression was used in ArcGIS with a maximum p-value for variable significance set at 0.3.

#### 4.4.2.4 *Assessment of models*

All regression models must be tested for their validity – their explanatory power – and their conformity to certain statistical assumption before the results can be applied to a population. The models were assessed for their explanatory power and their validity against the criteria shown in Table 4.8. The data points for the dependent variable (N = 46) were also found to be approximately normally distributed, another key assumption.

**Table 4.8 Regression assumptions and the relevant diagnostics (adapted from Field 2005, and Rosenshein, Scott, and Pratt 2011).**

| Assumption | Description | Diagnostic used | Critical value |
|---|---|---|---|
| No multicollineariy | The predictor variables should not correlate too highly | VIF - Variance Inflation | > 7.5 |
| Homoscedacity | At each level of the predictor variables, the level of variance in the residual terms should be constant | Kroenker's BP | p < 0.05 shows heteroscedacity |
| Indpendent Errors | The residiuals in the model should not be autocorrelated - ie adjacent residual should not be similar, which would suggest a misspecified model (possible missing variables) | Durban Watson (autocorrelation of adjecent residuals), Moran's I (spatial autocorrelation of residuals) | Below approximately 2 shows autocorrelation - see Appendix for exact values |
| Normally distributed errors | Residuals shiould show a normal distribution in a properly specified model | Jarque Bera | p < 0.05 shows lack of normality |
| Validity | The model should expain a large proportion of the variance in the independent variable, and the addition of variables should lead to significant improvement in the model, allowing for complexity of the model and avoiding over fitting (a rule of thumb is that there should be 10-15 datapoints for each independent variable) | Adjusted coefficient of determination (Adj R2), Akaike information criterion - corrected (AICc), F-test | For F test, p > 0.05 taken to confirm null hypothesis that model is invalid |

The models were also entered as Geographically Weighted Regression (GWR) in ArcMap. This was carried out as a supplement to the test for spatial autocorrelation. Although GWR should only be used once a properly specified Ordinary Least Squares model is obtained, it the spatial distribution of the surface coefficients can be a useful analytically in determining missing variables (Rosenshein et al. 2011).

## 4.5 Scenarios

The aim of the scenarios step in the modelling was to test the effect of projected demographic development in Trondheim using a model developed in the regression step of model development. The regression function chosen for use in the scenario modelling was the following:

**Average emissions (g/day) = 104 + 0.11*Centre Distance + 310*Accessibility with public transport**

This regression model fulfilled the following criteria: it had significant p-values and normality of residuals (in the absence of *sone* 34, a possible outlier). It contained two urban form variables, which are the variables of interest to this study, and the theoretical foundations for these two variables – centre distance and access to public transport – are strong (see Section 2).

The baseline scenario was based on demographic projections supplied by Trondheim municipality, which they had carried out using a combination of demographic forecasting by Statistikk Sentral Byrå and the municipalities own predications for building development using a model called KOMPASS. The projections form part of a regional plan for coming decades, the Trans-municipality Area Plan (*Interkommunalarealplan (*IKAP)) and show a population of around 220 000 by 2030. The building projections used as part of these demographic projections are shown in Figure 4.7. The *sone* demarcations and numbers are overlaid so that the reader can see in which *sone* the largest developments are planned.

The shading gives an indication of the estimated number of residential units in each of the planned new developments.

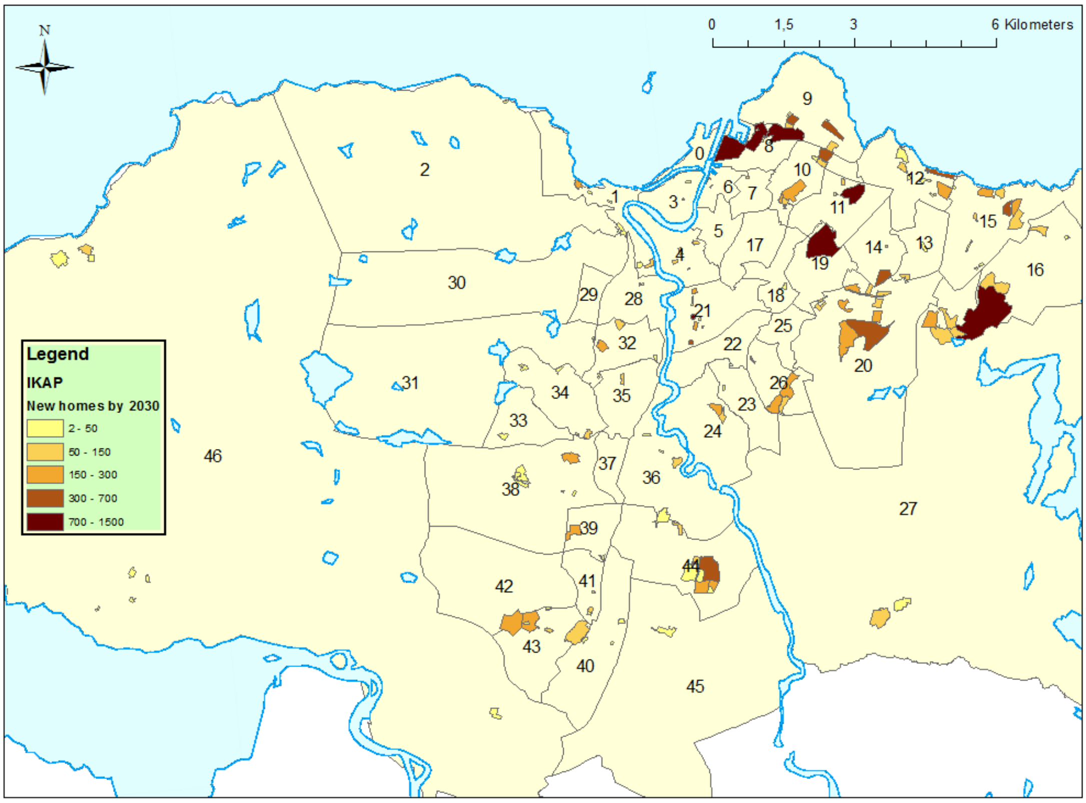


Figure 4.7 Planned building of new homes 2010–2030

Using the Norwegian average for households per capita, 2.2, an assessment was made of the contribution of new build to the projected growth in each *sone* in the baseline scenario (Statistisk sentralbyrå 2011). Two further scenarios were constructed on this basis. The centralisation scenario took the projected population in the year 2030 and moved around one third of the marginal growth from 2010 (approximately 16 000 of 48 000 people) from areas in the lowest quartile of per capita emissions according to the regression model (in particular those *sone* containing large residential property developments under the IKAP plan) and to *soner* in the lowest quartile on the emissions scale. In the dispersal scenario, the opposite process was assumed to take place. Growth in the lowest emitting quartile of *soner* was restricted and instead moved to the more highly polluting outer suburbs. Appendix VI shows the changes in marginal population growth assumed in each scenario. It should be noted that under the centralisation scenario it was assumed that *sone* 0, currently an uninhabited port area, would be used for residential development.

Three further scenarios were constructed by assuming a citywide improvement in accessibility by public transport, with the average ratio of connectivity by public transport to connectivity by car reduced by 0.5 in all *soner*. The baseline, centralisation and dispersal scenarios were modelled again under the new transport conditions.

Table 4.9 Summary of scenarios

| **Scenario** | **Description** |
|---|---|
| Baseline | Population increases in areas projected by municipl IKAP plan |
| Centralisation | Concentration of population increase in central sone, reduced in suburbs |
| Dispersal | Reduced population increase in centre, increased in suburbs |
| Transport | Baseline scenario plus city-wide increase in accessibility by public transport compared to car |
| Transport centralisation | Centralisation plus city-wide increase in accessibility by public transport compared to car |
| Transport dispersal | Dispersal plus city-wide increase in accessibility by public transport compared to car |

## 4.6 Model summary

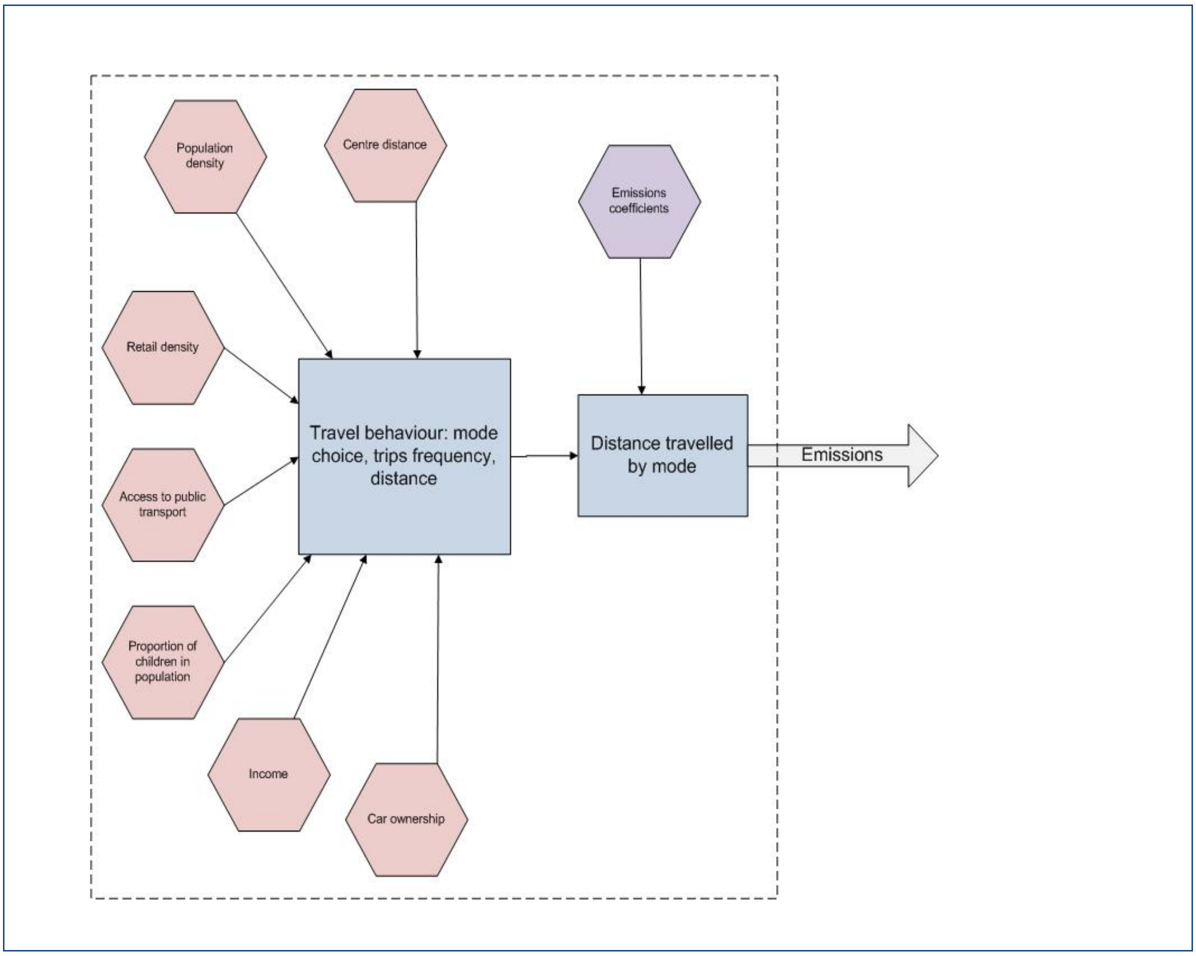


Figure 4.8 Drivers and processes for emissions from sone

Figure 4.8 summarises the configuration of the model for emissions from each geographic *sone*. The emissions shown in the arrow to the right in the figure are established as average emissions per capita in modelling step 1. The hexagons are model parameters established in the regression modelling, step 2. The idea in step 3, scenarios, is to establish changes in model parameters, such as a change in the populations of the *soner*, in order to model the consequences for total emissions in Trondheim.

# 5 Results and analysis

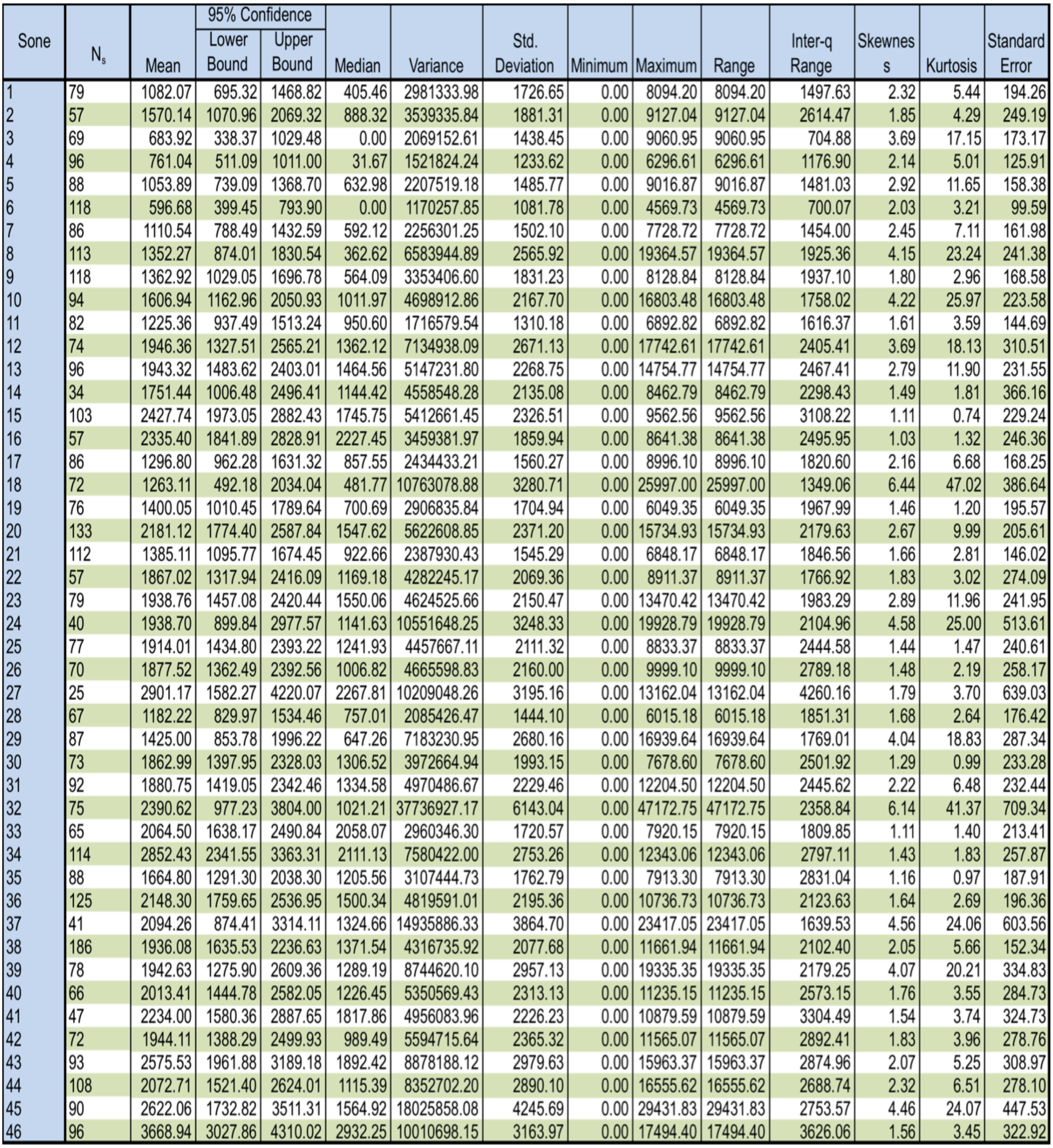
The exploratory nature of this study makes it more suitable for results and analysis to be presented together.

## 5.1 Average emissions

### 5.1.1 Average emissions per traveller

Table 5.1 shows the average emissions per traveller for each *sone* together with the most relevant descriptive statistics. This does not take into account non-travellers so cannot be taken to represent average emissions per capita.

**Table 5.1 Average emissions per traveller per day (g CO2e)**



| Sone | $N_s$ | Mean | 95% Confidence | | Median | Variance | Std. Deviation | Minimum | Maximum | Range | Inter-q Range | Skewness | Kurtosis | Standard Error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Lower Bound | Upper Bound | | | | | | | | | | |
| 1 | 79 | 1082.07 | 695.32 | 1468.82 | 405.46 | 2981333.98 | 1726.65 | 0.00 | 8094.20 | 8094.20 | 1497.63 | 2.32 | 5.44 | 194.26 |
| 2 | 57 | 1570.14 | 1070.96 | 2069.32 | 888.32 | 3539335.84 | 1881.31 | 0.00 | 9127.04 | 9127.04 | 2614.47 | 1.85 | 4.29 | 249.19 |
| 3 | 69 | 683.92 | 338.37 | 1029.48 | 0.00 | 2069152.61 | 1438.45 | 0.00 | 9060.95 | 9060.95 | 704.88 | 3.69 | 17.15 | 173.17 |
| 4 | 96 | 761.04 | 511.09 | 1011.00 | 31.67 | 1521824.24 | 1233.62 | 0.00 | 6296.61 | 6296.61 | 1176.90 | 2.14 | 5.01 | 125.91 |
| 5 | 88 | 1053.89 | 739.09 | 1368.70 | 632.98 | 2207519.18 | 1485.77 | 0.00 | 9016.87 | 9016.87 | 1481.03 | 2.92 | 11.65 | 158.38 |
| 6 | 118 | 596.68 | 399.45 | 793.90 | 0.00 | 1170257.85 | 1081.78 | 0.00 | 4569.73 | 4569.73 | 700.07 | 2.03 | 3.21 | 99.59 |
| 7 | 86 | 1110.54 | 788.49 | 1432.59 | 592.12 | 2256301.25 | 1502.10 | 0.00 | 7728.72 | 7728.72 | 1454.00 | 2.45 | 7.11 | 161.98 |
| 8 | 113 | 1352.27 | 874.01 | 1830.54 | 362.62 | 6583944.89 | 2565.92 | 0.00 | 19364.57 | 19364.57 | 1925.36 | 4.15 | 23.24 | 241.38 |
| 9 | 118 | 1362.92 | 1029.05 | 1696.78 | 564.09 | 3353406.60 | 1831.23 | 0.00 | 8128.84 | 8128.84 | 1937.10 | 1.80 | 2.96 | 168.58 |
| 10 | 94 | 1606.94 | 1162.96 | 2050.93 | 1011.97 | 4698912.86 | 2167.70 | 0.00 | 16803.48 | 16803.48 | 1758.02 | 4.22 | 25.97 | 223.58 |
| 11 | 82 | 1225.36 | 937.49 | 1513.24 | 950.60 | 1716579.54 | 1310.18 | 0.00 | 6892.82 | 6892.82 | 1616.37 | 1.61 | 3.59 | 144.69 |
| 12 | 74 | 1946.36 | 1327.51 | 2565.21 | 1362.12 | 7134938.09 | 2671.13 | 0.00 | 17742.61 | 17742.61 | 2405.41 | 3.69 | 18.13 | 310.51 |
| 13 | 96 | 1943.32 | 1483.62 | 2403.01 | 1464.56 | 5147231.80 | 2268.75 | 0.00 | 14754.77 | 14754.77 | 2467.41 | 2.79 | 11.90 | 231.55 |
| 14 | 34 | 1751.44 | 1006.48 | 2496.41 | 1144.42 | 4558548.28 | 2135.08 | 0.00 | 8462.79 | 8462.79 | 2298.43 | 1.49 | 1.81 | 366.16 |
| 15 | 103 | 2427.74 | 1973.05 | 2882.43 | 1745.75 | 5412661.45 | 2326.51 | 0.00 | 9562.56 | 9562.56 | 3108.22 | 1.11 | 0.74 | 229.24 |
| 16 | 57 | 2335.40 | 1841.89 | 2828.91 | 2227.45 | 3459381.97 | 1859.94 | 0.00 | 8641.38 | 8641.38 | 2495.95 | 1.03 | 1.32 | 246.36 |
| 17 | 86 | 1296.80 | 962.28 | 1631.32 | 857.55 | 2434433.21 | 1560.27 | 0.00 | 8996.10 | 8996.10 | 1820.60 | 2.16 | 6.68 | 168.25 |
| 18 | 72 | 1263.11 | 492.18 | 2034.04 | 481.77 | 10763078.88 | 3280.71 | 0.00 | 25997.00 | 25997.00 | 1349.06 | 6.44 | 47.02 | 386.64 |
| 19 | 76 | 1400.05 | 1010.45 | 1789.64 | 700.69 | 2906835.84 | 1704.94 | 0.00 | 6049.35 | 6049.35 | 1967.99 | 1.46 | 1.20 | 195.57 |
| 20 | 133 | 2181.12 | 1774.40 | 2587.84 | 1547.62 | 5622608.85 | 2371.20 | 0.00 | 15734.93 | 15734.93 | 2179.63 | 2.67 | 9.99 | 205.61 |
| 21 | 112 | 1385.11 | 1095.77 | 1674.45 | 922.66 | 2387930.43 | 1545.29 | 0.00 | 6848.17 | 6848.17 | 1846.56 | 1.66 | 2.81 | 146.02 |
| 22 | 57 | 1867.02 | 1317.94 | 2416.09 | 1169.18 | 4282245.17 | 2069.36 | 0.00 | 8911.37 | 8911.37 | 1766.92 | 1.83 | 3.02 | 274.09 |
| 23 | 79 | 1938.76 | 1457.08 | 2420.44 | 1550.06 | 4624525.66 | 2150.47 | 0.00 | 13470.42 | 13470.42 | 1983.29 | 2.89 | 11.96 | 241.95 |
| 24 | 40 | 1938.70 | 899.84 | 2977.57 | 1141.63 | 10551648.25 | 3248.33 | 0.00 | 19928.79 | 19928.79 | 2104.96 | 4.58 | 25.00 | 513.61 |
| 25 | 77 | 1914.01 | 1434.80 | 2393.22 | 1241.93 | 4457667.11 | 2111.32 | 0.00 | 8833.37 | 8833.37 | 2444.58 | 1.44 | 1.47 | 240.61 |
| 26 | 70 | 1877.52 | 1362.49 | 2392.56 | 1006.82 | 4665598.83 | 2160.00 | 0.00 | 9999.10 | 9999.10 | 2789.18 | 1.48 | 2.19 | 258.17 |
| 27 | 25 | 2901.17 | 1582.27 | 4220.07 | 2267.81 | 10209048.26 | 3195.16 | 0.00 | 13162.04 | 13162.04 | 4260.16 | 1.79 | 3.70 | 639.03 |
| 28 | 67 | 1182.22 | 829.97 | 1534.46 | 757.01 | 2085426.47 | 1444.10 | 0.00 | 6015.18 | 6015.18 | 1851.31 | 1.68 | 2.64 | 176.42 |
| 29 | 87 | 1425.00 | 853.78 | 1996.22 | 647.26 | 7183230.95 | 2680.16 | 0.00 | 16939.64 | 16939.64 | 1769.01 | 4.04 | 18.83 | 287.34 |
| 30 | 73 | 1862.99 | 1397.95 | 2328.03 | 1306.52 | 3972664.94 | 1993.15 | 0.00 | 7678.60 | 7678.60 | 2501.92 | 1.29 | 0.99 | 233.28 |
| 31 | 92 | 1880.75 | 1419.05 | 2342.46 | 1334.58 | 4970486.67 | 2229.46 | 0.00 | 12204.50 | 12204.50 | 2445.62 | 2.22 | 6.48 | 232.44 |
| 32 | 75 | 2390.62 | 977.23 | 3804.00 | 1021.21 | 37736927.17 | 6143.04 | 0.00 | 47172.75 | 47172.75 | 2358.84 | 6.14 | 41.37 | 709.34 |
| 33 | 65 | 2064.50 | 1638.17 | 2490.84 | 2058.07 | 2960346.30 | 1720.57 | 0.00 | 7920.15 | 7920.15 | 1809.85 | 1.11 | 1.40 | 213.41 |
| 34 | 114 | 2852.43 | 2341.55 | 3363.31 | 2111.13 | 7580422.00 | 2753.26 | 0.00 | 12343.06 | 12343.06 | 2797.11 | 1.43 | 1.83 | 257.87 |
| 35 | 88 | 1664.80 | 1291.30 | 2038.30 | 1205.56 | 3107444.73 | 1762.79 | 0.00 | 7913.30 | 7913.30 | 2831.04 | 1.16 | 0.97 | 187.91 |
| 36 | 125 | 2148.30 | 1759.65 | 2536.95 | 1500.34 | 4819591.01 | 2195.36 | 0.00 | 10736.73 | 10736.73 | 2123.63 | 1.64 | 2.69 | 196.36 |
| 37 | 41 | 2094.26 | 874.41 | 3314.11 | 1324.66 | 14935886.33 | 3864.70 | 0.00 | 23417.05 | 23417.05 | 1639.53 | 4.56 | 24.06 | 603.56 |
| 38 | 186 | 1936.08 | 1635.53 | 2236.63 | 1371.54 | 4316735.92 | 2077.68 | 0.00 | 11661.94 | 11661.94 | 2102.40 | 2.05 | 5.66 | 152.34 |
| 39 | 78 | 1942.63 | 1275.90 | 2609.36 | 1289.19 | 8744620.10 | 2957.13 | 0.00 | 19335.35 | 19335.35 | 2179.25 | 4.07 | 20.21 | 334.83 |
| 40 | 66 | 2013.41 | 1444.78 | 2582.05 | 1226.45 | 5350569.43 | 2313.13 | 0.00 | 11235.15 | 11235.15 | 2573.15 | 1.76 | 3.55 | 284.73 |
| 41 | 47 | 2234.00 | 1580.36 | 2887.65 | 1817.86 | 4956083.96 | 2226.23 | 0.00 | 10879.59 | 10879.59 | 3304.49 | 1.54 | 3.74 | 324.73 |
| 42 | 72 | 1944.11 | 1388.29 | 2499.93 | 989.49 | 5594715.64 | 2365.32 | 0.00 | 11565.07 | 11565.07 | 2892.41 | 1.83 | 3.96 | 278.76 |
| 43 | 93 | 2575.53 | 1961.88 | 3189.18 | 1892.42 | 8878188.12 | 2979.63 | 0.00 | 15963.37 | 15963.37 | 2874.96 | 2.07 | 5.25 | 308.97 |
| 44 | 108 | 2072.71 | 1521.40 | 2624.01 | 1115.39 | 8352702.20 | 2890.10 | 0.00 | 16555.62 | 16555.62 | 2688.74 | 2.32 | 6.51 | 278.10 |
| 45 | 90 | 2622.06 | 1732.82 | 3511.31 | 1564.92 | 18025858.08 | 4245.69 | 0.00 | 29431.83 | 29431.83 | 2753.57 | 4.46 | 24.07 | 447.53 |
| 46 | 96 | 3668.94 | 3027.86 | 4310.02 | 2932.25 | 10010698.15 | 3163.97 | 0.00 | 17494.40 | 17494.40 | 3626.06 | 1.56 | 3.45 | 322.92 |

An analysis of variance procedure shows that there is a significant variance in the means for these figures, as shown in Table 5.2.

Table 5.2 ANOVA test for significance of mean differences in average traveller emissions

| Emission | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Sone | 1452407452,756 | 45 | 32275721,172 | 5,469 | ,000 |
| Within Sone | 22471293896,807 | 3808 | 5901075,078 | | |
| Total | 23923701349,564 | 3853 | | | |

However, the there are large standard errors and confidence intervals ascribed to the mean values (99.59 ≤ SEM ≤ 639.03). The confidence intervals for the means (α=0.05) are shown in Figure 5.1. It is also of note that all *soner* show a positive skew (1.03 ≤ $g_1$ ≤6.44) – that is the mean value is based on a sampling distribution with a right-skewed tail.

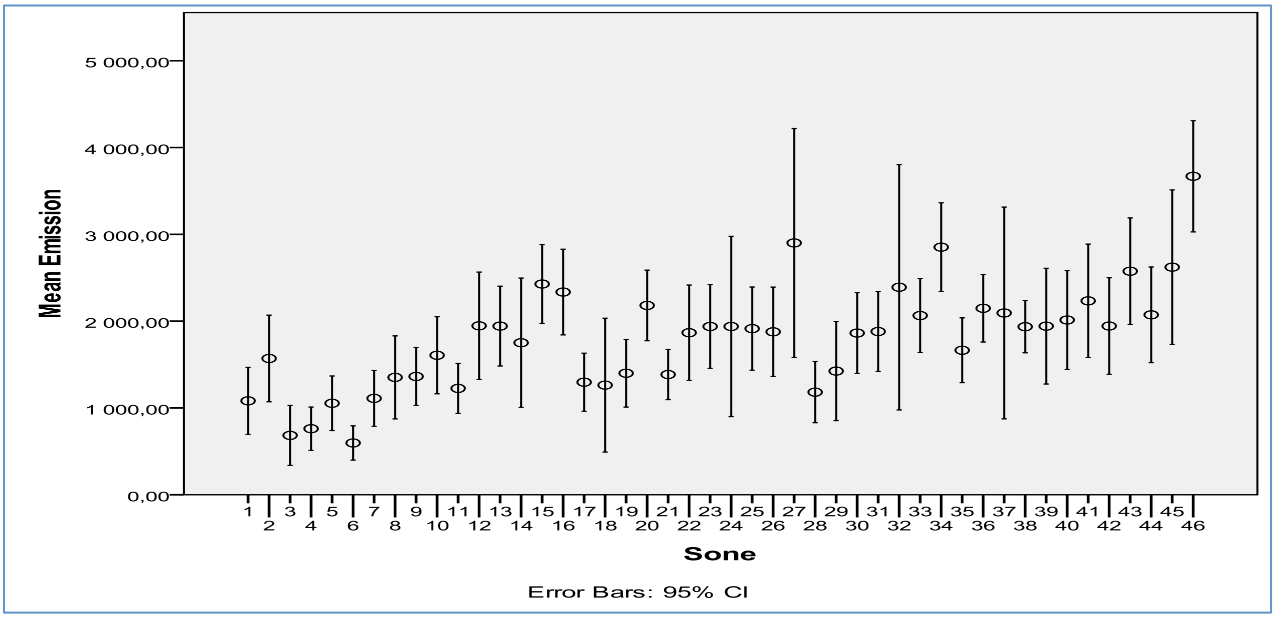
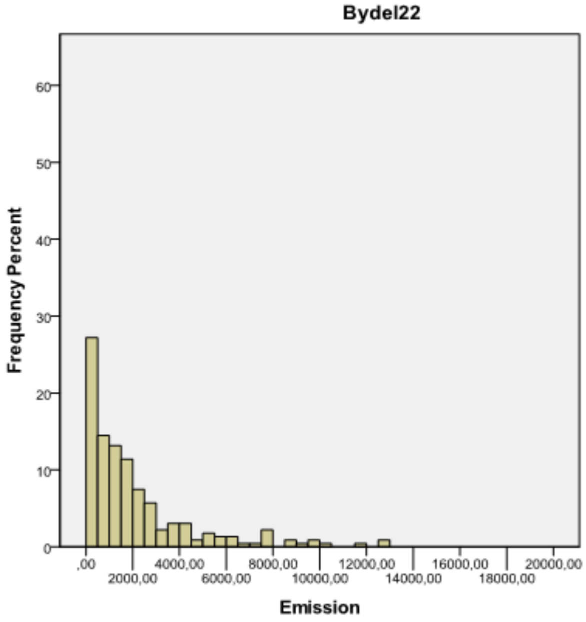


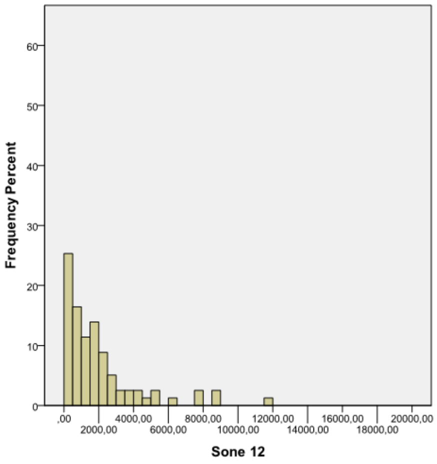
Figure 5.1 Confidence intervals for mean traveller emissions (g CO2e)

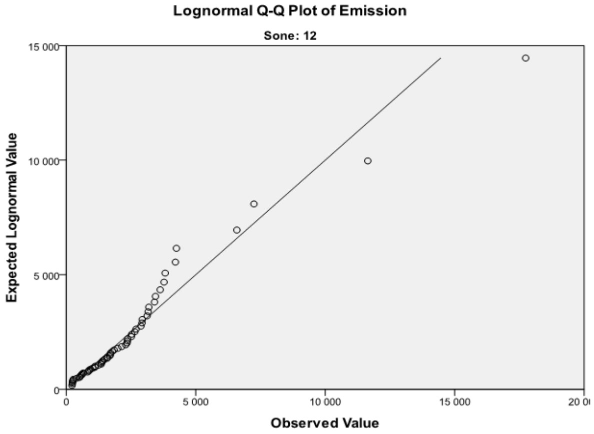
#### 5.1.1.1 Uncertainty in average traveller emission per geographical unit

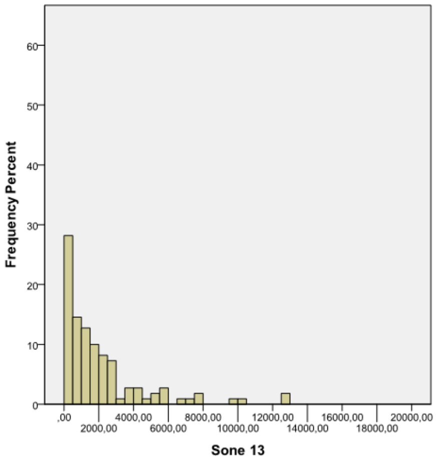
Considerable effort was put into establishing the causes of the uncertainties in the average traveller emissions values and the results of this analysis will be presented here because it provides insight into the meaning of this average figure and some of the statistical challenges and limitations of this type of model. Figure 5.2 shows relative frequency histograms for a family of geographical units within the Trondheim area: the *grunnkretser* can be thought of as nesting inside the *soner*, which in turn are contained within the *delområde*.

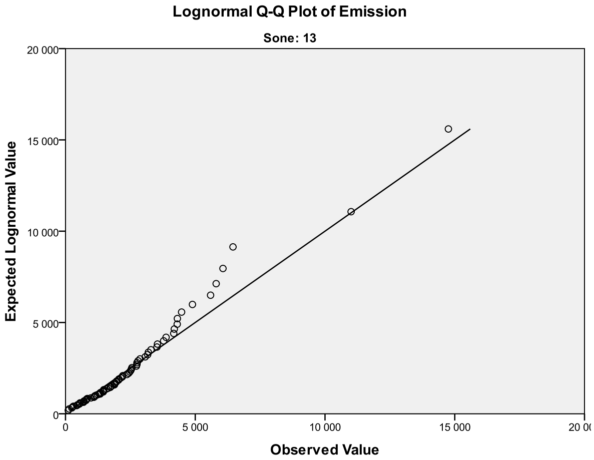
| Bydel | Sone | GK |
|---|---|---|
| 22 | 12 | 16012201 |
| | | 16012202 |
| | | 16012203 |
| | | 16012204 |
| | | 16012205 |
| | | 16012206 |
| | | 16012207 |
| | | 16012209 |
| | 13 | 16012210 |
| | | 16012211 |
| | | 16012212 |
| | | 16012216 |
| | | 16012217 |
| | 14 | 16012208 |
| | | 16012215 |
| | | 16012218 |
| | | 16012219 |
| | | 16012220 |

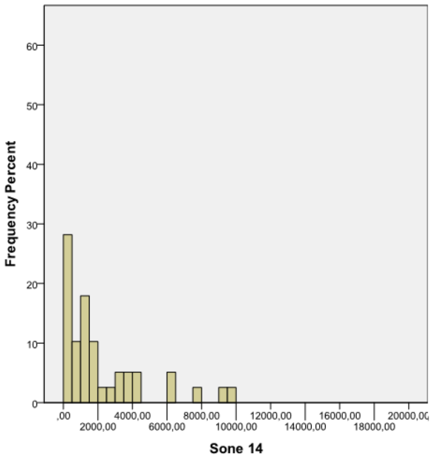












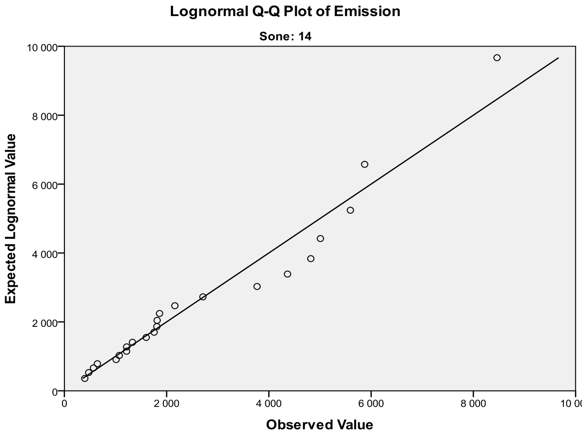


Figure 5.2 Frequency histograms for an example delområde, 22, and the soner contained within it. Also shown are the Q-Q plots for the values above zero in each sone against a lognormal distribution

Two things are clear from visual inspection of these histograms. Firstly, the emissions profile of each area does not follow a normal distribution and, secondly, the increase in the sample size causes an increasing adherence towards a right-skewed, long-tailed type of distribution, as was indicated by the skewness shown in Table 5.1. The grunnkrets histograms are not shown for reasons of space, but it is clear that as the size of the geographical unit increase (from *grunnkrets* to *delområde*) the adherence of the distribution to a uniformity increases with the increasing sample size.

A standard method for dealing with uncertainty in non-normally distributed samples is to convert them using either a log or some other form of transformation. There were three challenges for this approach in this study.

Firstly, the frequency distribution shown in Figure 5.2 is not only not normal but also bimodal. This may not be apparent on first inspection, but in each distribution the mode is zero. Not only are individuals that produce emissions the most frequent type of traveller, but also their emissions profile is described by a separate probability distribution to those travellers that use emitting forms of transport. This probability is the binomial distribution between choosing a polluting mode of transport or not. The emissions of those travelling, on the other hand, are described by the probability distribution that results in the heavily, right-skewed distribution evident in Figure 5.2.

Secondly, when using right-skewed data it is most common to use the geometric mean (that is the arithmetic mean of the transformed data), which corresponds to the median of the original sample as a way of describing central location. Once the data is transformed, the median and the geometric mean are approximately the same and confidence intervals can be estimated using standard statistical methods. The median is often recommended as a more representative for right-tailed distributions, because of the potential for data values at the end of the long tail to inflate the arithmetic mean. However, in this study, the arithmetic mean is required. Finding the median for each *sone* might be interesting for comparative purposes but it does not allow scaling up to a population level.

Thirdly, in addition to the emissions profile of those travelling, one also has to make allowances for those not travelling on any given day (in Trondheim about 14 per cent, see Section 4.3.5). This means that the sampling distribution of the eventual functional unit of this analysis will be trimodal. This will be discussed further in Section 6.1.

The sampling distributions of the emitting travellers in each *sone* were plotted in probability plots for various distribution types in SPSS. The probability plots show the expected distribution as a straight line, with the data points from the sampling distribution deviating from this line to a greater or lesser extent. While the sampling distributions did not match any of the distribution types perfectly, they were most similar to the lognormal distribution.

Consulting the literature for a way to deal with the arithmetic mean of a lognormal distribution proved challenging because most authors recommended the use of the median, which is not so useful here, as described above. However, one study outlined four different approaches, of progressively more complex computational complexity (Armstrong 1992). The most relevant for this level of analysis was to use the t-statistic to calculate confidence intervals rather than the z-statistic. However, this approach is not reliable in samples with a large geometric standard deviation (the standard deviation distribution of the lognormally-transformed data points) above 4. Appendix VII and VIII show the geometric standard deviation, the arithmetic mean and the t-value required for finding a 95 per cent confidence interval.

The t-values established using this method were all over 2, larger than the 1.96 z-value used to establish the standard confidence intervals shown in Table 5.1. Therefore confidence intervals using the method for lognormal distributions are larger than those estimated using standard methods, which reflects the fact that the t-distribution is more widely dispersed than the z-distribution. With such wide confidence intervals, it can legitimately be asked how confident one can be with the result of the ANOVA test and how meaningful it is to use the travellers' emissions as the basis for the dependent variable in the following regression analysis. This will be discussed further in Section 6.1. Other methods of measuring variance and deviation were also considered. The average deviation has been suggested as a better measure of variation in distributions that are heavily right-skewed because the error terms are not squared, meaning that large values are less likely to inflate the variance.

### 5.1.2 Functional unit of emissions

Table 5.3 shows the average functional unit of emissions: average emissions per capita per day. $N_s$ is the number of travellers per *sone*, while $N_{nt,s}$ represents non-travellers (see Section 4.3). Figure 5.3 shows the spatial distribution of average emissions per person by *sone* in Trondheim.

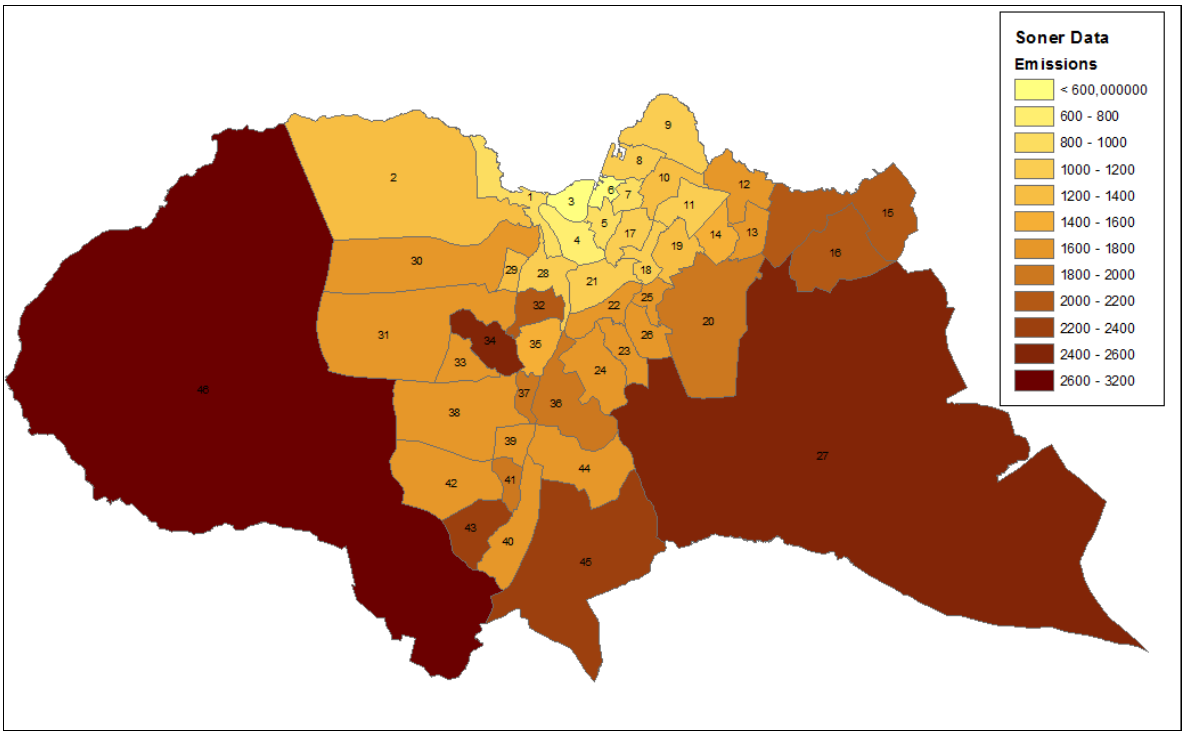


Figure 5.3 Spatial distribution of mean per capita daily emissions (g $CO_2e$)

Table 5.3 Functional unit of emissions

| Sone | Emissions (g CO$_2$e) | N$_s$ | N$_{nt,s}$ | Per capita emissions (g CO$_2$e) |
|---:|---:|---:|---:|---:|
| 1 | 85483,3909 | 79 | 13 | 930,58 |
| 2 | 89498,15567 | 57 | 9 | 1350,32 |
| 3 | 47190,64294 | 69 | 11 | 588,17 |
| 4 | 73060,03137 | 96 | 16 | 654,50 |
| 5 | 92742,41651 | 88 | 14 | 906,35 |
| 6 | 70408,17648 | 118 | 19 | 513,14 |
| 7 | 95506,39197 | 86 | 14 | 955,06 |
| 8 | 152807,0023 | 113 | 18 | 1162,96 |
| 9 | 160823,9956 | 118 | 19 | 1172,11 |
| 10 | 151052,6453 | 94 | 15 | 1381,97 |
| 11 | 100479,8775 | 82 | 13 | 1053,81 |
| 12 | 144030,5159 | 74 | 12 | 1673,87 |
| 13 | 186558,3671 | 96 | 16 | 1671,25 |
| 14 | 59549,0647 | 34 | 6 | 1506,24 |
| 15 | 250057,1295 | 103 | 17 | 2087,86 |
| 16 | 133117,9321 | 57 | 9 | 2008,45 |
| 17 | 111524,8244 | 86 | 14 | 1115,25 |
| 18 | 90943,71985 | 72 | 12 | 1086,27 |
| 19 | 106403,5759 | 76 | 12 | 1204,04 |
| 20 | 290089,0697 | 133 | 22 | 1875,76 |
| 21 | 155132,666 | 112 | 18 | 1191,20 |
| 22 | 106420,0484 | 57 | 9 | 1605,64 |
| 23 | 153161,9337 | 79 | 13 | 1667,33 |
| 24 | 77548,19784 | 40 | 7 | 1667,29 |
| 25 | 147379,0679 | 77 | 13 | 1646,05 |
| 26 | 131426,6058 | 70 | 11 | 1614,67 |
| 27 | 72529,30223 | 25 | 4 | 2495,01 |
| 28 | 79208,47295 | 67 | 11 | 1016,71 |
| 29 | 123975,212 | 87 | 14 | 1225,50 |
| 30 | 135998,3163 | 73 | 12 | 1602,17 |
| 31 | 173029,3043 | 92 | 15 | 1617,45 |
| 32 | 179296,3069 | 75 | 12 | 2055,93 |
| 33 | 134192,7956 | 65 | 11 | 1775,47 |
| 34 | 325176,61 | 114 | 19 | 2453,09 |
| 35 | 146502,2933 | 88 | 14 | 1431,73 |
| 36 | 268537,3387 | 125 | 20 | 1847,54 |
| 37 | 85864,66731 | 41 | 7 | 1801,06 |
| 38 | 360110,4019 | 186 | 30 | 1665,03 |
| 39 | 151525,2578 | 78 | 13 | 1670,66 |
| 40 | 132885,3127 | 66 | 11 | 1731,54 |
| 41 | 104998,2347 | 47 | 8 | 1921,24 |
| 42 | 139975,9975 | 72 | 12 | 1671,94 |
| 43 | 239524,1529 | 93 | 15 | 2214,95 |
| 44 | 223852,2356 | 108 | 18 | 1782,53 |
| 45 | 235985,7194 | 90 | 15 | 2254,97 |
| 46 | 352218,5084 | 96 | 16 | 3155,29 |

## 5.2 Linear regression

### 5.2.1 Correlations

Figure 5.4 shows a scatterplot of the variables established during model development, created in ArcMap, while Table 5.4 shows the correlation between variables established using SPSS, expressed as the Pearson product-moment correlation coefficient. As established in an earlier study (Loveland 2011) and predicted by the literature review in Section 2, centre distance shows a strong linear correlation with centre distance, reflected in a correlation coefficient of 0.867.

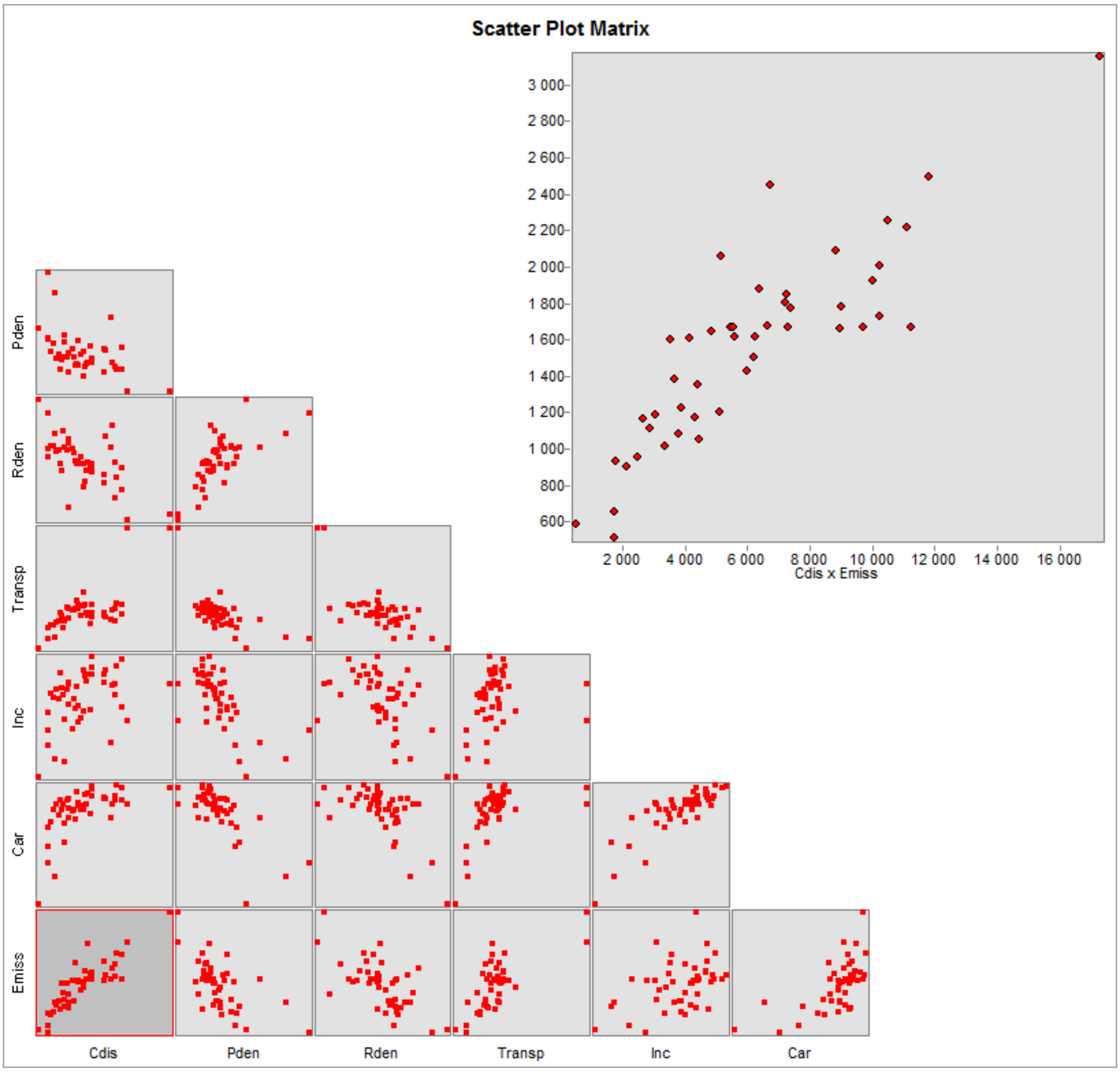
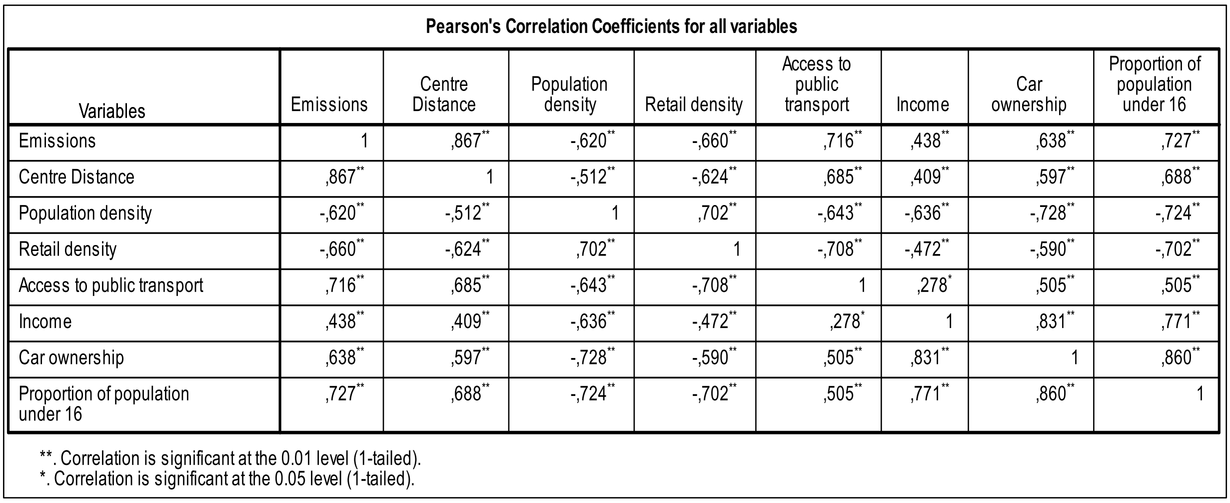


Figure 5.4 Scatterplot showing independent and dependent variables

Emissions show a fairly linear relationship with several of the other variables also. As theory would suggest, lower density areas show lower average emissions per capita: the correlation coefficient between inhabitants per square kilometre (*Pden*) and emissions is – 0.62. The retail density variable (*RDen*) also shows a negative correlation coefficient with emissions (–0.66), meaning that *soner* with a lower density of retail establishments have higher emissions although it should be remembered that this variable is on the logarithmic scale. The public transport variable (*Trans*), which is a ratio of average accessibility of a *sone* by public transport over its accessibility by car, also shows the expected relationship with a positive Pearson's coefficient of 0.716: areas with relatively long journey times by public transport have higher emissions, although there is a large degree of clustering at the midpoint of the accessibility scale.

**Table 5.4 Correlations between variables**



**Pearson's Correlation Coefficients for all variables**

| Variables | Emissions | Centre Distance | Population density | Retail density | Access to public transport | Income | Car ownership | Proportion of population under 16 |
|---|---|---|---|---|---|---|---|---|
| Emissions | 1 | ,867$^{**}$ | -,620$^{**}$ | -,660$^{**}$ | ,716$^{**}$ | ,438$^{**}$ | ,638$^{**}$ | ,727$^{**}$ |
| Centre Distance | ,867$^{**}$ | 1 | -,512$^{**}$ | -,624$^{**}$ | ,685$^{**}$ | ,409$^{**}$ | ,597$^{**}$ | ,688$^{**}$ |
| Population density | -,620$^{**}$ | -,512$^{**}$ | 1 | ,702$^{**}$ | -,643$^{**}$ | -,636$^{**}$ | -,728$^{**}$ | -,724$^{**}$ |
| Retail density | -,660$^{**}$ | -,624$^{**}$ | ,702$^{**}$ | 1 | -,708$^{**}$ | -,472$^{**}$ | -,590$^{**}$ | -,702$^{**}$ |
| Access to public transport | ,716$^{**}$ | ,685$^{**}$ | -,643$^{**}$ | -,708$^{**}$ | 1 | ,278$^{*}$ | ,505$^{**}$ | ,505$^{**}$ |
| Income | ,438$^{**}$ | ,409$^{**}$ | -,636$^{**}$ | -,472$^{**}$ | ,278$^{*}$ | 1 | ,831$^{**}$ | ,771$^{**}$ |
| Car ownership | ,638$^{**}$ | ,597$^{**}$ | -,728$^{**}$ | -,590$^{**}$ | ,505$^{**}$ | ,831$^{**}$ | 1 | ,860$^{**}$ |
| Proportion of population under 16 | ,727$^{**}$ | ,688$^{**}$ | -,724$^{**}$ | -,702$^{**}$ | ,505$^{**}$ | ,771$^{**}$ | ,860$^{**}$ | 1 |

$^{**}$. Correlation is significant at the 0.01 level (1-tailed).
$^{*}$. Correlation is significant at the 0.05 level (1-tailed).

The remaining independent variables – income, car ownership and proportion of population under the age of 16 – all show a positive correlation with average emissions, with correlation coefficients of 0.438, 0.638 and 0.727 respectively.  However, the spread of data points on the income curve indicates a fairly weak relationship and the relationship between car ownership and emissions appears to be slightly non-linear.

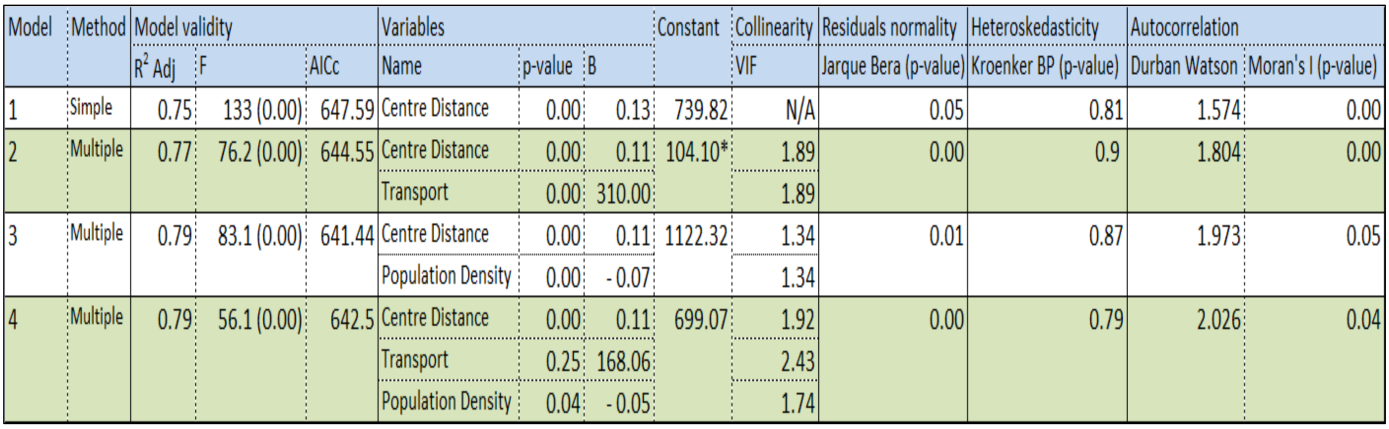
In addition to the correlations between the dependent variable and the independent variables, there is evidence of strong relationships between the dependent variables. In particular, many of the variables are correlated with centre distance.

### 5.2.2 Regressions models

Linear regression is an iterative process (Field 2005; Rosenshein et al. 2011) and the results of one stage of the analysis often lead to further avenues of exploration. The results of all the regression analyses attempted are not shown, therefore, but summarised in tabular form.

Table 5.5 summarises the parameters and diagnostic values for some of the key regression models examined according to the methodology outlined in Sections 4.4.2.2–4.4.2.3. Initially the independent variable was tested against the key variables of centre distance, access to public transport and population density.

**Table 5.5 Key regression models**



| Model | Method | Model validity | | | Variables | | | Constant | Collinearity | Residuals normality | Heteroskedasticity | Autocorrelation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $R^2$ Adj | F | AICc | Name | p-value | B | | VIF | Jarque Bera (p-value) | Kroenker BP (p-value) | Durban Watson | Moran's I (p-value) |
| 1 | Simple | 0.75 | 133 (0.00) | 647.59 | Centre Distance | 0.00 | 0.13 | 739.82 | N/A | 0.05 | 0.81 | 1.574 | 0.00 |
| 2 | Multiple | 0.77 | 76.2 (0.00) | 644.55 | Centre Distance | 0.00 | 0.11 | 104.10* | 1.89 | 0.00 | 0.9 | 1.804 | 0.00 |
| | | | | | Transport | 0.00 | 310.00 | | 1.89 | | | | |
| 3 | Multiple | 0.79 | 83.1 (0.00) | 641.44 | Centre Distance | 0.00 | 0.11 | 1122.32 | 1.34 | 0.01 | 0.87 | 1.973 | 0.05 |
| | | | | | Population Density | 0.00 | -0.07 | | 1.34 | | | | |
| 4 | Multiple | 0.79 | 56.1 (0.00) | 642.5 | Centre Distance | 0.00 | 0.11 | 699.07 | 1.92 | 0.00 | 0.79 | 2.026 | 0.04 |
| | | | | | Transport | 0.25 | 168.06 | | 2.43 | | | | |
| | | | | | Population Density | 0.04 | -0.05 | | 1.74 | | | | |

#### 5.2.2.1 *Model validity*

The simple regression using centre distance as the dependent variable explained 75 per cent of the variation in average emissions per *sone* ($r^2$ = 0.75, p = 0.00). Adding population density and accessibility by public transport as secondary variables improved the validity of the model somewhat ($r^2$ adj is 0.79 and 0.77 respectively) with each variable found to be significant (p = 0.00). Adding both of these variables simultaneously did not result in an improvement to the validity of the model ($r^2$ adj = 0.79) and resulted in the public transport variable becoming insignificant (p = 0.24).

As described in Section 4.4.2.3, the exploratory regression function in ArcMap was used to combine all possible variables. *The upper threshold for explaining the variance in the dependent variable was confirmed to be around 79 per cent, where three variables were included.* The addition of further variables did not result in a significant increase in the explanatory power of the model. The reasons for this lack of improvement in the explanatory power of the model will be covered in the discussion. Exploratory regression results are found in Appendix IX.

### 5.2.2.2 Conformity with regression assumptions

The diagnostics in Table 5.5 measure the conformity of each model to the assumptions behind linear regression.

#### 5.2.2.2.1 Normality of residuals

All models returned non-normal residuals, as is evidenced by the significance of the Jarque-Bera p-values, which tests the null hypothesis that residuals follow a normal distribution.

However, if one looks at the plot of standardised residuals against standardised expected values (see Figure 5.5 for example residual, P-P and residual histogram plots for model 3) it is clear that one particular *sone,* 34,has residuals that lie more than 3 standard deviations from the regression curve. This is also evident in the map of emissions in Section 5.1.2.

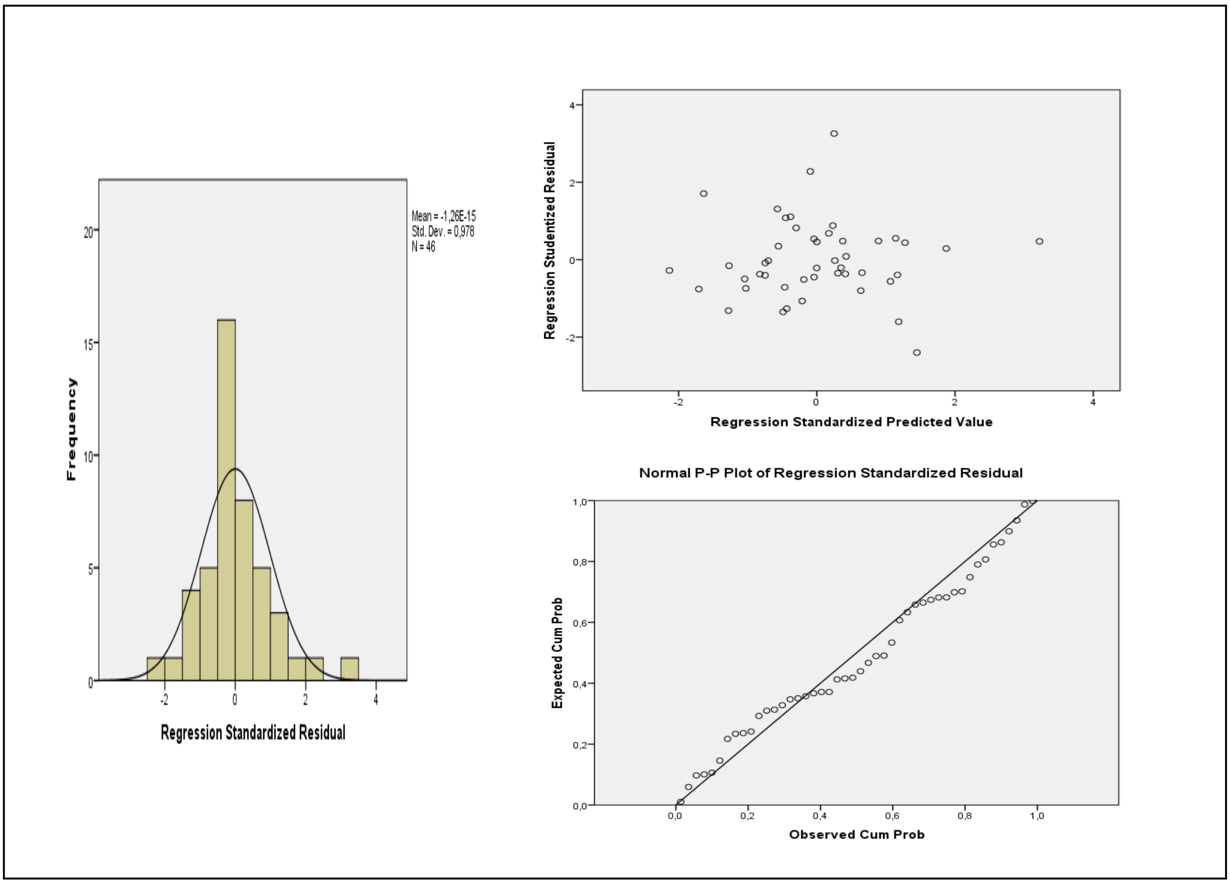
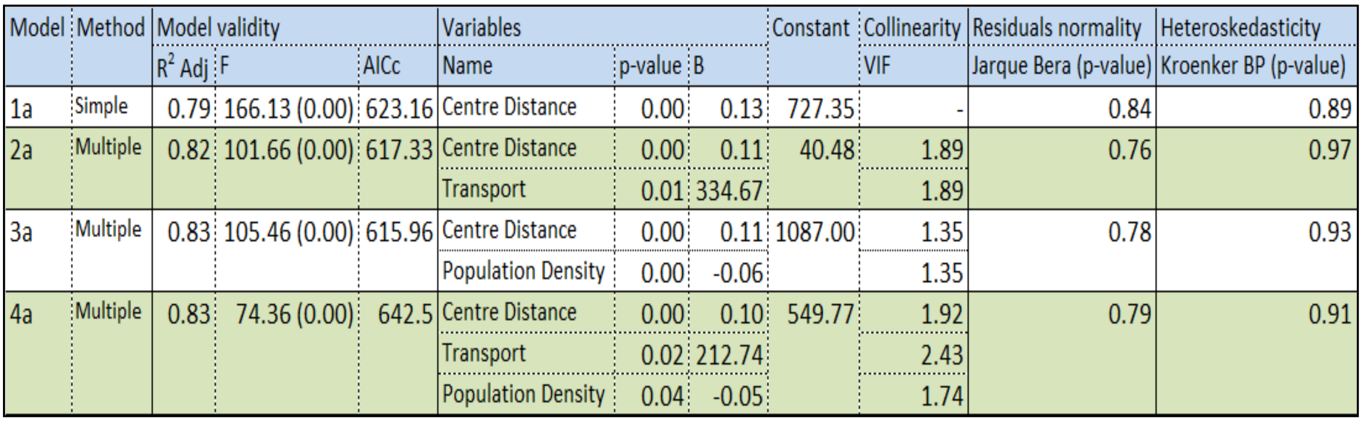


Figure 5.5 Residual plots for model 3, possible outlier more than three standard deviations from zero

In order to check whether the non-normality of the residuals was as a result of that particular *sone*, several of the models listed were rerun without that data point (i.e. N = 45). This resulted in models with very similar parameters but non-significant Jarque-Bera statistics, see Table 5.6.

Table 5.6 Regression models with sone 34 removed from data set



| Model | Method | Model validity | | | Variables | | | Constant | Collinearity | Residuals normality | Heteroskedasticity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $R^2$ Adj | F | AICc | Name | p-value | B | | VIF | Jarque Bera (p-value) | Kroenker BP (p-value) |
| 1a | Simple | 0.79 | 166.13 (0.00) | 623.16 | Centre Distance | 0.00 | 0.13 | 727.35 | - | 0.84 | 0.89 |
| 2a | Multiple | 0.82 | 101.66 (0.00) | 617.33 | Centre Distance | 0.00 | 0.11 | 40.48 | 1.89 | 0.76 | 0.97 |
| | | | | | Transport | 0.01 | 334.67 | | 1.89 | | |
| 3a | Multiple | 0.83 | 105.46 (0.00) | 615.96 | Centre Distance | 0.00 | 0.11 | 1087.00 | 1.35 | 0.78 | 0.93 |
| | | | | | Population Density | 0.00 | -0.06 | | 1.35 | | |
| 4a | Multiple | 0.83 | 74.36 (0.00) | 642.5 | Centre Distance | 0.00 | 0.10 | 549.77 | 1.92 | 0.79 | 0.91 |
| | | | | | Transport | 0.02 | 212.74 | | 2.43 | | |
| | | | | | Population Density | 0.04 | -0.05 | | 1.74 | | |

We can conclude that it is probable that the emissions value for *sone* 34 is causing the residuals in the regression models to be distributed non-normally. Removing that data point also improves the explanatory power of the model, shown by a higher adjusted $R^2$ value. However, it is interesting to note that the presence or otherwise of that data point has little bearing on the model parameters. This was confirmed by further diagnostic tests, such as Cook's and Mahalhoni's distance.

It is not possible to conclude that the emissions value for *sone* 34 is an outlier. It may be that an unknown variable is responsible for high emissions in that area. This will be considered further in the discussion (Section 6).

##### *5.2.2.2.2 Homoscedasticy*

A well-specified and accurate linear model should show constant variance of residuals. The Kroenker BP p-values in Table 5.5 are all above 0.05, meaning that it is unlikely that the models selected have a level of heteroscedasticity that would lead to inaccurate standard errors of the model parameters. However, visual inspection of the residuals plots (see Figure 5.5) did suggest some variability in the variance of the residuals.

##### *5.2.2.2.3 Autocorrelation*

The Durban Watson value in Table 5.5 tests the null hypothesis that the residuals in the regression are not autocorrelated. The significance of a Durban Watson value is dependent on k', the number of independent variables. Using the table provided in Appendix X, we can confirm the null hypothesis that the residuals are not serially autocorrelated in models 1 to 4.

However, the Moran's I p-values for all of the models are significant ($p \leq 0.05$). This is evidence of a degree of *spatial* autocorrelation, and this finding would appear to be backed by visual examination of the clustering of residuals, as shown in Figure 5.6.

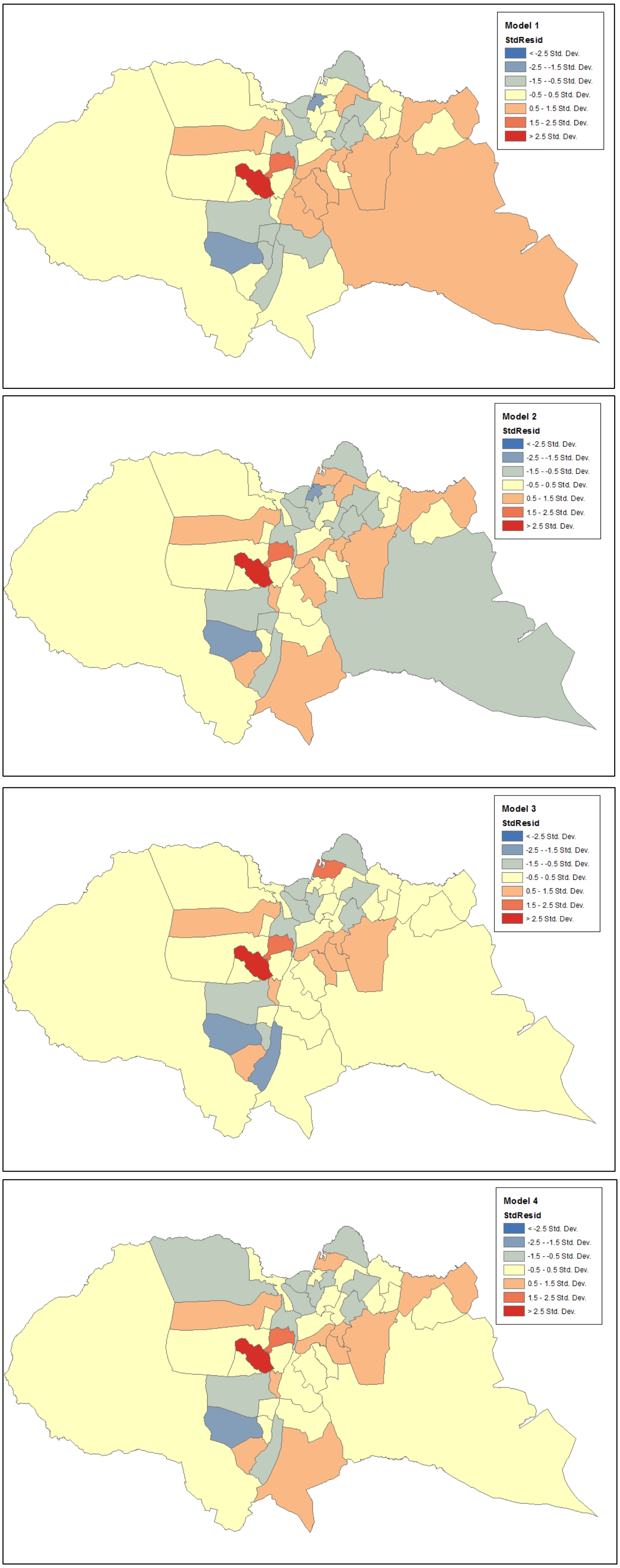
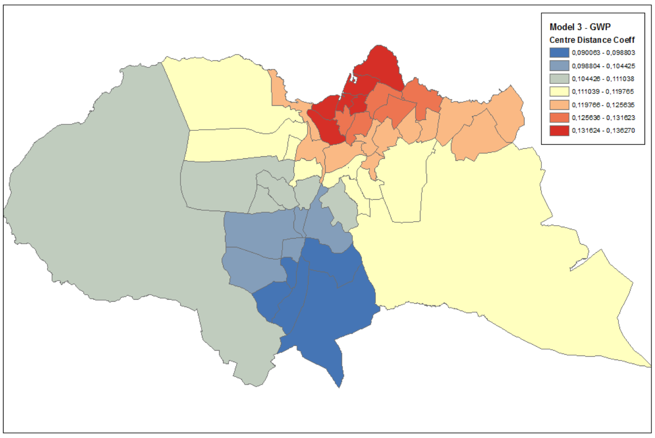
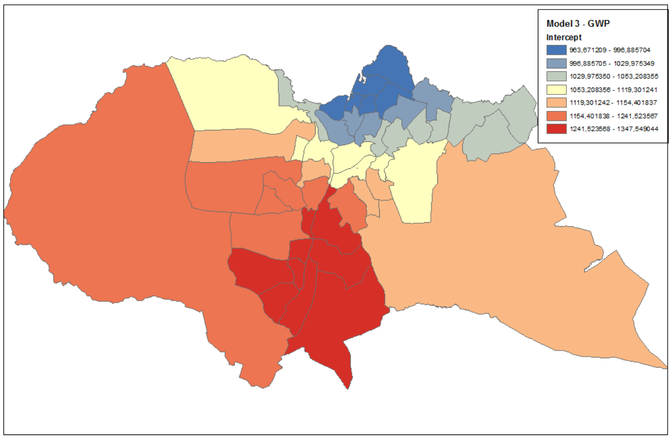


Figure 5.6 Residuals maps for regression models 1 to 4, indicating a degree of spatial autocorrelation

#### *5.2.2.2.4 Geographically weighted regression*

Figure 5.7 shows the GWP results for Model 3.





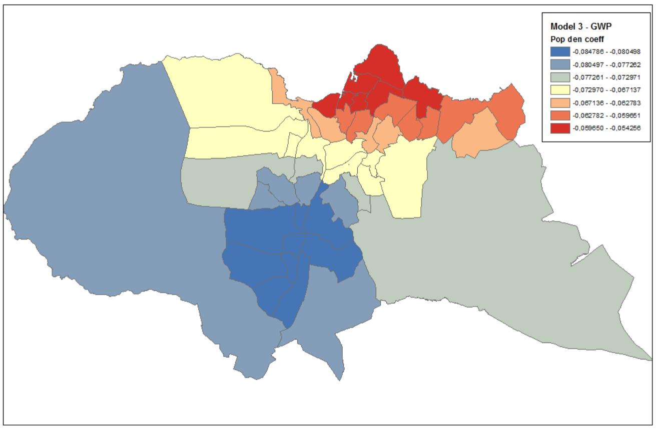


**Figure 5.7 Coefficient surface maps for Model 3. From left to right, centre distance, intercept (constant) and population density.**

The highly clustered variation in the values of the coefficients is indicative of misspecification in the underlying ordinary least squares regression. The formal results of the GWP should therefore not be used (Rosenshein et al. 2011) but the surface coefficients shown above do serve a useful analytical purpose in confirming the results of the spatial autocorrelation results. Both results show a high degree of clustering in the centre of the town and to the south. This suggests that an underlying spatial process is at work on the dependent variable (emissions) that is currently missing from the model. The diagnostics for multicollinearity (VIF) shown in Table 5.6 suggest that the correlation between independent variables does not adversely affect the models.

## 5.3 Scenarios

Presented here are the results of emissions projections for Trondheim in 2030 under the five scenarios outlined in Section 4.5: baseline, centralisation, decentralisation, transport improvement, transport improvement with centralisation and transport improvement with decentralisation. Table 5.7 presents a summary of the modelled results

Table 5.7 Scenarios results

| Scenario | Baseline | Central | Disperse | Transport | Transport central | Transport disperse |
|---|---|---|---|---|---|---|
| Total 2030 (tonnes per year) | 124613.29 | 118558.97 | 130017.24 | 112187.86 | 106133.54 | 117591.81 |
| Margin 2010-2030 (tonnes per year) | 27930.97 | 21876.65 | 33334.92 | 15505.54 | 9451.22 | 20909.49 |
| Margin as percentage | 28.9% | 22.6% | 34.5% | 16.0% | 9.8% | 21.6% |
| Margin as percentage of baseline margin | 0.0% | -21.7% | 19.3% | -44.5% | -66.2% | -25.1% |
| Total as percentage of baseline total | 0.0% | -4.9% | 4.3% | -10.0% | -14.8% | -5.6% |

Figure 5.8 shows total emissions in Trondheim in 2030 in all five scenarios. All scenarios show an increase in emissions, with the dispersal scenario highest and the transport centralisation scenario lowest.

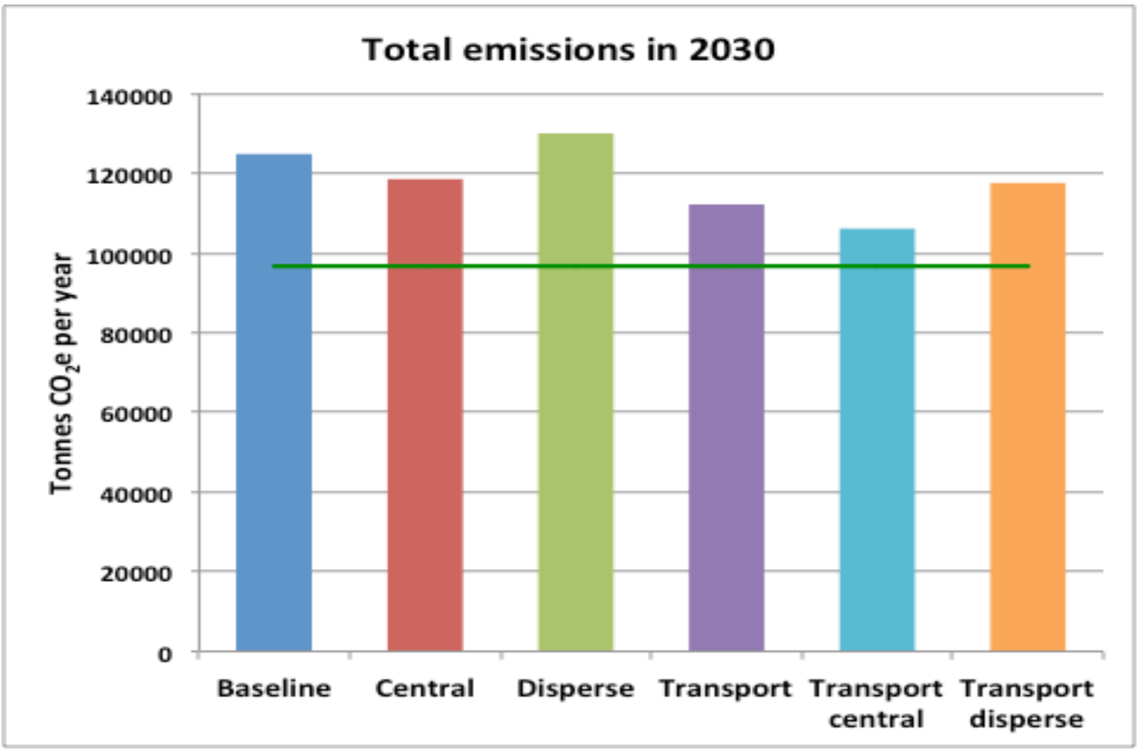


Figure 5.8 Total modelled emissions for Trondheim in 2030 in 5 different scenarios

Figure 5.9 shows the marginal change in emissions in 2030 compared to 2010 levels, which shows the differences between scenarios more clearly.

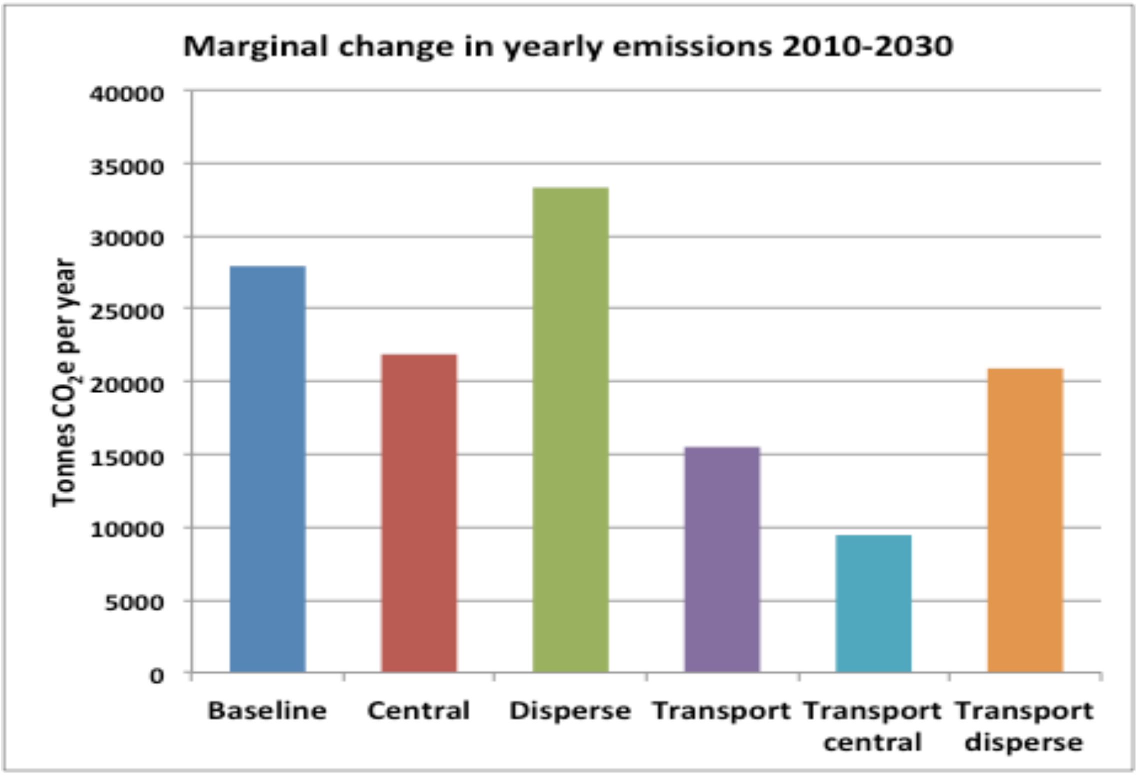


Figure 5.9 The increase in yearly emissions in Trondheim between 2010 and 2030

Figure 5.10 shows the marginal change in yearly emissions between 2010 and 2030 as a percentage deviation from the baseline scenario. This brings into focus the differences between the scenarios. The dispersal scenario results in yearly emissions increase that is 20 per cent larger than the baseline scenario. The transport scenarios all result in in margins that are substantially smaller than the baseline increase.

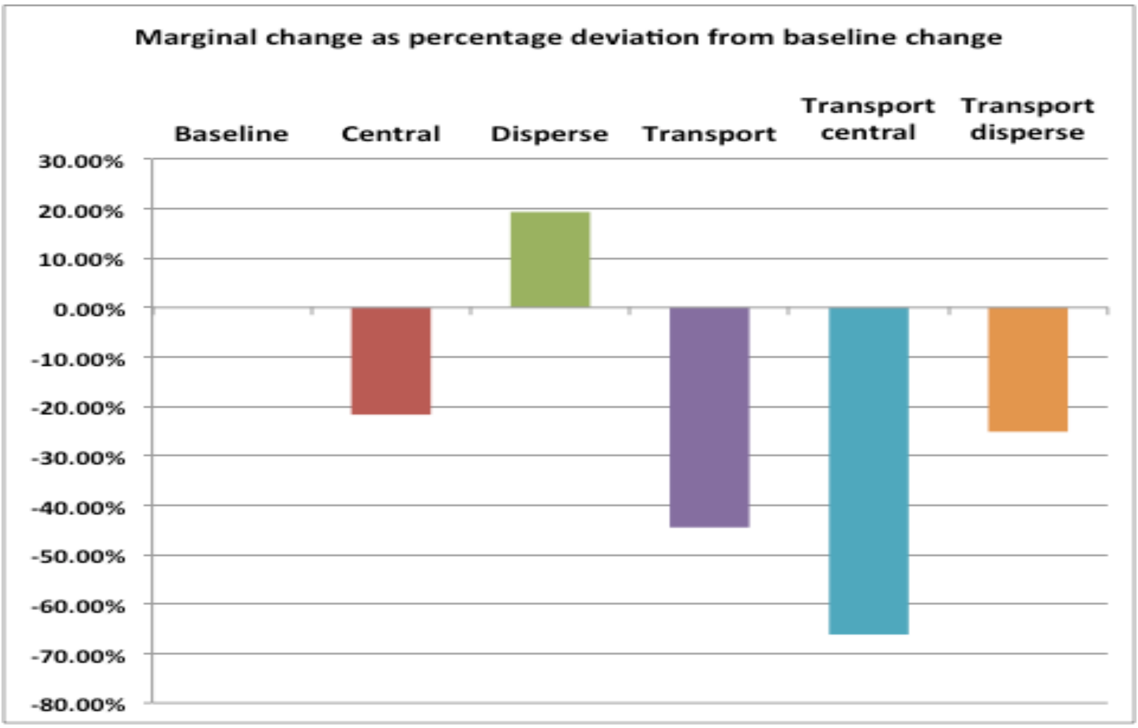


Figure 5.10 The deviation from the baseline margin as a percentage in all other scenarios

# 6 Discussion

The discussion section will discuss the results for each modelling step in turn, together with sources of uncertainty and suggestions for model improvements and future work. The results of the scenarios modelling step will be considered last, which will lead logically into a discussion of the implications of this study for decision makers.

## 6.1 Emissions

The results from the emissions modelling show that there is wide variation in daily emissions from personal transport in Trondheim. The highest daily per capita emissions of 3155 g $CO_2$e in *sone* 46 is more than six times higher than that in the lowest emitting *sone* (513 g $C0_2$e per day in *sone* 6). This in itself is an interesting if not entirely unexpected finding. Many previous studies (for example Næss 2009; Engebretsen 2005a; Ewing & Cervero 2010) have shown that travel behaviour varies with location in terms of trip frequency, mode choice and trip distance, and it is logical to assume that these variations have consequences for emissions. From visual inspection of the map of average emissions (Figure 5.3) we can see that average emissions in Trondheim have similar spatial variation to those in Toronto and Melbourne (see Figures 2.3 and 2.4 in Section 2): areas closer to the city centre have lower emissions, while those areas on the outskirts of the city have higher emissions.

### 6.1.1 Emissions: sources of uncertainty, and model improvements

As mentioned in the literature review, the average emission per capita for a geographical area is a composite variable describing the mode choice, trip frequency and trip distance in a parametric sample of a population, combined with mode-specific emissions coefficients, within a single value. Such a composite variable has many sources of error or uncertainty.

Firstly, the basis of the parametric sample, the RVU data, may in itself contain errors or be biased. It is conceivable that certain types of people will respond to travel surveys while others are less likely, and that these two groups of people exhibit different types of travel behaviour. For example, people who are worried about environmental pollution and modify their own travel behaviour as a result may be more likely to respond to a travel survey than those that have no such concerns. This may partly explain why total emissions calculated from the RVU data and scaled up to an annual figure come to approximately 100 kilotonnes, less than the SSB figure for emissions from car traffic of 139 kilotonnes (Trondheim Kommune 2008). A further source of uncertainty is that the RVU data is weighted according to the day of the week each particular respondent travelled in order to make the survey as a whole more representative of a typical day's travel in Norway. It may be however that this weighting system is distortive at a finer geographical resolution.

Secondly, the emissions coefficients were chosen to be as representative as possible for the average trip in Trondheim. However, the actual emissions for each trip would vary according to many factors that cannot be accounted for in this study: the actual vehicle used, the traffic conditions gradient and driving style of the particular driver and so on. In future work emissions coefficients could be calibrated against fuel purchase and vehicle fleet data in Trondheim, if available.

Thirdly, there is uncertainty in the representativeness of the sample for each *sone*. In the analysis of the average emissions results, it was discovered that the distribution of emissions in each *sone* sample is not normal. A large proportion of individuals either do not travel or use non-emitting modes for all of their trips. Those who use emitting modes for some or all of their trips produce a heavily right-skewed emissions curve. While this non-normality is not necessarily a formal, mathematical problem for the regression analysis in step two, it does present some challenges for estimating the uncertainty in the average values, while at the same time revealing something about the nature of "typical" travel behaviour for a particular geographic population-

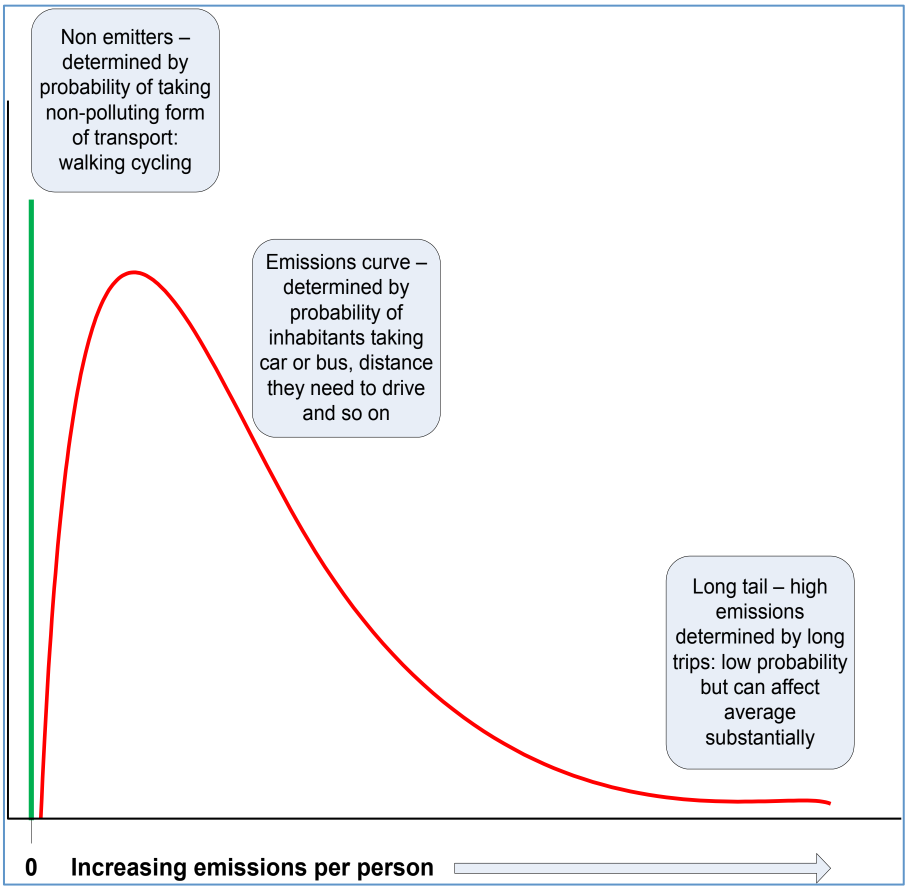


Figure 6.1 Stylized emissions profile for a fictional geographical area

Figure 6.1 shows a stylised distribution of emissions for a non-specific geographical area, based on the frequency histograms found during the analysis in Section 5.1, with an interpretation of what the different parts of the curve represent.

One can see that the largest proportion of individuals in a particular area is represented at the far left of the figure with zero emissions. These are in fact two groups of individuals: firstly, those individuals who do not travel and secondly those that do travel but choose to do so by non-polluting modes such as walking or cycling. It should be reiterated that the proportion of non-travellers in each *sone* was assumed to be the Trondheim average (based on the RVU data) and this assumption may be invalid: there may be actual variation in the proportion of non-travellers in each *sone*.

The lognormal-type curve represents individuals who undertake at least some of their trips by emitting forms of transport. The steep rise in the lognormal-type curve shows that while very short emitting trips are quite unlikely, there is a rapid rise in the probability of individuals emitting amounts towards the left hand side of the distribution curve. Thereafter the curve declines fairly rapidly – it becomes less and less likely for an individual to emit at increasing amounts. However, the right-skewed nature of the curve means that there are individuals on any given day who travel long distances by emitting modes of transport.

This is a source of uncertainty in the arithmetic average used for the functional unit. However, it also appears to be a reasonable reflection of reality. It is conceivable on any given day that small number of people may need to travel to and from work several times – perhaps they need to collect a sick child from nursery, deliver them to a relative, return to work, realise they left their mobile telephone at the relative’s house, return to the relative’s house, return to work and so on. Such examples may seem trivial but they provide insight into the reason why the distribution curve of emissions has a long tail. It also means it is difficult to decide that a particular individual’s emissions comprise an outlier in the data.

In the analysis of average emissions by those travelling in Section 5.1, standard statistical procedures were used to establish confidence intervals and standard errors for the average values. The size of these confidence intervals was very large (the standard errors on which the confidence intervals were based varied between 100 and 709 g $CO_2$e). In addition, other methods were sought that were more suitable for non-normal distributions, and hence confidence intervals. The methods obtained found confidence intervals ($\alpha = 0.95$) that were even larger than those using standard methods. Part of the reason for these large confidence intervals may be that the long tail in a right-skewed distribution has a variance inflationary property. Values to the right of the distribution can result in a very large variance due to the squaring of error terms in the calculation of variance using the standard technique, i.e. $(\bar{x}-x)^2$. Hence, even *soner* with large numbers of respondents returning a large sample size can show large variances and hence uncertainties. It may be that another method of measuring variance might be more relevant here, such as average deviation, or mean average deviation. The uncertainty around the representativeness of the average emissions value for each *sone* also has relevance for the regression-modelling step, and will be retuned to in Section 6.2.

Fourthly, the use of averages of spatial data brings particular challenges, briefly outlined in the literature review. The modifiable area unit problem describes the phenomenon whereby averages for spatially distributed data aggregation are susceptible to a scale effect and a zonal effect (Wong & Lee 2005). The former occurs because an average at a high level of spatial aggregation (for example county-level crime rates) may disguise important variation within that zone (street-level crime rates). The zonal effect occurs because any polygon can be divided into an infinite number of smaller polygons: the average value for a particular point in space for a particular variable will therefore depend on the borders of the polygon in ends up in. Taken together the zonal and scale effects of the modifiable area unit problem lead to the danger of the so-called ecological fallacy and can distort the results of statistical analysis. The choice of *sone* is the geographical unit of analysis was made partly in response to these concerns. They are small enough to provide an insight into the spatial variation of emissions in Trondheim, thereby avoiding the dangers of the scaling effect by over-aggregation, while at the same time providing a reasonable sample size (the concerns outlined in the previous paragraph notwithstanding). In terms of the zonal effect, the fact that *soner* were constructed by the geography department at the NTNU with specific goal of creating a homogenous geo-social spatial unit was felt to be beneficial in that regard. Nevertheless, it may well be that important variations in emissions have been missed because of the choice of geographical unit in this study.

## 6.2 Regression

The results of the regression analyses show clearly that distance to the town centre is the most dependent variable predicting the average level of emissions in each *sone*. Using centre distance alone explains approximately 75 per cent of the variability in average emissions per *sone* ($r^2 = 0.75$ in a simple regression).

The other six variables do not lead to a drastic improvement in the validity of the model, and addition of more than three variables in the model is counterproductive, in that models configured with three or more variables do not explain a greater proportion of the variability in the dependent variable.

The variables that do lead to a model improvement are neighbourhood population density, proportion of population under 16 and effectiveness of public transport. Combinations of these variables increase the validity of the model to around 77–79 per cent. (Adjusted $R^2$ is between 0.77 and 0.79). However, combining the three urban form variables produces a model where the latter variable, transport, is insignificant ($p = 0.24$). It is to be expected in a sense that a model containing many explanatory variables would be difficult to obtain, given the risk of over-fitting: with the independent variable being based on a sample of 46 observations, the maximum number of independent variables would be around 3 using the rule of thumb that there should be 10–15 items of data for each independent variable (Field 2005).

It is interesting to not that the most effective variables in the regression model were mostly those that describe spatial variation in land use or urban form. This runs counter to those who argue that land use and urban form are not statistically significant predictors of travel behaviour and therefore transport emissions (see for example (Boarnet & Sarmiento 1998; Ewing & Cervero 2010). However, none of the variables lead to a *substantial* improvement in the explanatory validity of the model above centre distance. There are several reasons why this might be the case. Firstly, the amount of error and uncertainty in the estimation of the dependent variable might limit the effectiveness of the model. Secondly, the model may be misspecified in several ways: explanatory variables may be missing, measuring the wrong thing or inaccurate in themselves. Thirdly, linear regression itself may not be the best tool to analyse spatial variation in emissions. These three aspects of the regression model will be considered in more detail in the following section.

### 6.2.1 Regression: sources of uncertainty, and model improvements

The sources of uncertainty in the measurement of the dependent variable were discussed in Section 6.1. In the context of the regression analysis, this uncertainty is important, as it will make up a certain proportion of the residuals, thus resulting in regression model parameters that are unreliable. The fact that the dependent variable estimation is drawn from a non-normal distribution is of particular significance, as it increases the uncertainty in the estimation of the dependent variable and makes estimating the true value of that uncertainty difficult. Figure 5.1 showing the confidence intervals for the average emissions of travellers is a good illustration of this. As (Lewis & Linzer 2005) put it: “if the sampling uncertainty in the dependent variable is not constant across observations, the regression errors will be heteroscedastic and ordinary least squares (OLS) will introduce further inefficiency and may produce inconsistent standard error estimates.” Interestingly, although the plots of residuals against expected values appeared to show heteroscedasticity (see Figure 5.5) the Kroenker BP values were not found to be significant. This requires further investigation. One further possible avenue of further work would be to apply weighted regression to the analysis, whereby the dependent variable data points are weighted according to their level of uncertainty. This was attempted at an early stage in this study, after the student was advised to use the s*one* sample size as weighting value. However, this was abandoned as it appeared not to improve the model and, in addition, it became increasingly clear that the uncertainty in the average emissions was not only dependent on the sample size, but also the length of the emissions distribution tail. Furthermore, Lewis and Linzer advise that simple weighted regression will not be effective unless uncertainty in the measurement of dependent variable is responsible for a very high proportion of the size of the residuals, and suggest several more effective alternatives, which may present avenues of future work (2005).

The diagnostics used in the analysis of the regression models suggest that the linear regression models may be misspecified. Firstly, all regression models returned non-normal residuals, with highly significant Jacque Bera values ($p \leq 0.05$, see Table 5.5). As shown in the analysis in Section 5.2.2.2.1, this could be resolved by removing *sone* 34 from the analysis, suggesting that this *sone* may represent an outlier. However, closer inspection of the data used to estimate average emissions for *sone* 34 shows a reasonable sample size ($N_s$= 114), an emissions distribution tail that is not particularly long (maximum = 12341 g, skewness = 1.43). So an alternative to the hypothesis that *sone* 34 represents an outlier is that it is an area of Trondheim with genuinely high emissions, and that the explanatory variables currently employed are not able to explain this high value.

Further evidence for misspecification of the model is provided by the consistent spatial autocorrelation of the residual terms. Spatial autocorrelation is good evidence for either missing explanatory variables or a non-linear relationship between the variables (Rosenshein et al. 2011). Closer inspection of the residuals maps (see Figure 5.6) shows consistent spatial autocorrelation of negative residuals in the centre of Trondheim: the regression models tend to overestimate emissions levels. This is supported by the use of geographically weighted regression as an exploratory tool. The coefficient surfaces show a clear spatial pattern, with clustering in the centre of the town. Further work is required to uncover the cause of these spatial patterns in the regression residuals and coefficient surfaces.

One further possible source of misspecification is error in the independent variables. Centre distance was easily established through a network calculation, but the increasing size of the *sone* polygons towards the edge of the Trondheim area means that the average value becomes less representative of the travel distance to the town centre for all residents of the *sone*. Retail density is measured as number of retail outlets per square kilometre in each *sone*, but this does not allow for the fact that residents may well use outlets in other *sone*, especially if they are geographically closer. This is an example of the ecological fallacy. A better measure could be the number retail outlets within a specific distance of the centre of each *sone*. It would also be more meaningful to take into account the size of the retail outlet (large supermarket or small corner store, for example). Income and car ownership were based on the RVU data itself, and the accuracy of the regression model would be improved with access to the non-parametric data at the required geographic resolution from the Statistisk Sentral Byrå.

Other modelling alternatives to ordinary least squares regression exist that could not be fully explored given the time constraints on this study. Geographically weighted regression could produce a better model for predictions once a properly specified linear model were obtained (Rosenshein et al. 2011). Other alternative for using data with unusual distributions in the dependent variable are generalised regression or robust regression analysis (Atkinson & Riani 2000). In addition, the tri-modal nature of the emissions distribution for each *sone* suggests that the distributions can be thought of as being determined by a series of different probability distributions, as discussed in Section 6.1. This might make the system a candidate for the kind of multi-level mixed modelling used by Bhat & Zhao (2002) for example. This might allow for the choice between emitting and non-emitting modes of transport to be modelled by a binomial function, for example, and the distribution curve for emitting travellers could be treated separately. A working hypothesis would be that the change in binomial distribution between emitting and non emitting modes of transport would lead to fewer individuals with zero emissions at greater distance from the town centre, while the log normal curve describing emitting individuals would flatten and skew further to the right with distance, lower access to public transport and so on. This is partly born out by exploratory work on the shape of *delområde* emissions curves, shown in Appendix XI.

## 6.3 Scenarios

Total emissions are found to be above 2010 levels in all the scenarios modelled for Trondheim in 2030. This a result of the large increase in population expected – from around 170 000 to around 220 000, or approximately 30 per cent. The baseline scenario is derived from the IKAP projections, which are themselves based on Trondheim's fairly stringent regulations to regulate urban sprawl. Under these circumstances the modelled growth in emissions is to around 128 per cent of 2010 levels, or roughly in line with population growth. The centralisation scenario shows that if even more stringent centralisation policies were followed, and around a third of the projected growth in population moved from *sone* with high emissions profiles to central areas with lower emission profiles, absolute emissions would be 5 per cent lower in 2030 than under the baseline scenario, which is in line with one study which looked at scenarios of projected urban development and transport emissions in the UK (Mitchell et al. 2011). This represents a 20 per cent improvement on the baseline margin of the projected increase in emissions. Conversely, if building developments are allowed to occur more heavily in higher emitting *sone*, absolute emissions would be 5 per cent higher than under the baseline scenario, a 20 per cent increase on the baseline marginal.

The scenario results show that increasing the effectiveness of public transport in relation to car transport would have a major impact on future emissions, with deviations from the baseline marginal increase of approximately –45, – 66 and – 35 per cent for the transport, transport centralisation and transport decentralisation scenarios respectively.

Under the most favourable scenario, transport centralisation, absolute emissions are still projected to be higher, by about 10 per cent, in 2030 than in 2010. This suggests that planning and infrastructure changes cannot in themselves achieve emissions reductions in themselves in the face of large population growth. However, given the relative permanence of human settlements once established, it is important to note that he spatial planning of Trondheim's future will have important consequences for its long term emissions profile. If policy-makers decide to follow a dispersal scenario, the town would in effect be locked in to a higher emissions profile for many decades to come.

### 6.3.1 Scenarios: sources of uncertainty and model improvements

First of all it must be clearly stated that the results of the scenarios modelling should be treated with extreme caution. The regression function used has a fairly high validity ($r^2$ adj = 0.77) but much of the actual variability in emissions is not accounted for. In addition, the intercept of 104 was fount to be insignificant, which may be a result of the fact that a zero value for the transport variable is meaningless (the ratio of travel time by public transport to travel by car cannot in reality be zero). Nevertheless, given that several regression models provided similar validity with different variables, it was in part a question of choosing a regression model that would provide results regarding parameters of interest.  Given that the focus for this research is the effect of planning and urban form characteristics on emissions, it seemed reasonable to choose a model that contained two of these variables.

It is important to point out what the model does not account for.  Technological changes are likely to reduce per kilometre emissions from passenger transport in the coming decades (Kahn Ribeiro et al. 2007).  Other policy instruments such as road pricing or parking charges are not taken into account.  In addition, the increase in the relative accessibility of public transport assumes that in the course of those changes the emissions coefficient for public transport remains constant.  In reality increasing service cover might increase the emissions per passenger kilometre due to an increase in buses carrying small numbers of passengers. Conversely, a city-wide increase in the efficiency of the public transport system might lead to a nonlinear increase in passenger numbers, thus reducing the emissions coefficient.  Such nuances are not controlled for in the model.

There is much potential for the improving the scenarios modelling in future work.  Feedbacks within the model and integration with the Kompass model of demographic change would allow for year-by-year results and the integration of changing values of the independent variables.  For example, population density could be included as a variable in the regression function if population growth and changes in residential area values could be modelled dynamically year-on-year.  Similarly, improvements in the fuel efficiency of vehicles could be modelled dynamically by changing the vehicle emissions coefficients.

# 7 Conclusion

The findings of this thesis, based on the research question outlined in Section 1 are:

- The division of Trondheim into 46 *soner*, based on the smaller unit of *grunnkrets*, provides a level of geographical for spatial analysis of emissions from residential transportation that is analytically useful. However, uncertainty remains about the error terms for average emissions in each *sone*;

- Linear regression has been used to show that the majority of the variability in spatial emissions in Trondheim can be explained by household distance from the town centre. Other independent variables do not substantially improve the validity of the model, but diagnostically valid models can be obtained that include population density and access to public transport as variables. Analysis of the regression models suggest that at present unknown variables may be important to the improved accuracy of the models and methods other than linear regression should also be considered in future work;

- Projections for 2030 using a regression function incorporating centre distance and access to public transport show that in all scenarios considered emissions would increase in absolute terms, with emissions increasing in line with population in the baseline scenario. The model showed that centralisation of new demographic growth would result in 5 per cent lower absolute emissions in 2030 compared to the baseline, while dispersal would result in approximately 5 per cent higher absolute emissions. Improvement to public transport would consolidate emissions reduction, limiting marginal increase to 10 per cent from 2010 levels, according to the model.

- For policy makers, this study suggests that any one planning policy can have marginal influence on overall emissions, but that in combination planning policies can reduce the size of emissions increases even in the face of large population growth.

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# 9 Appendices

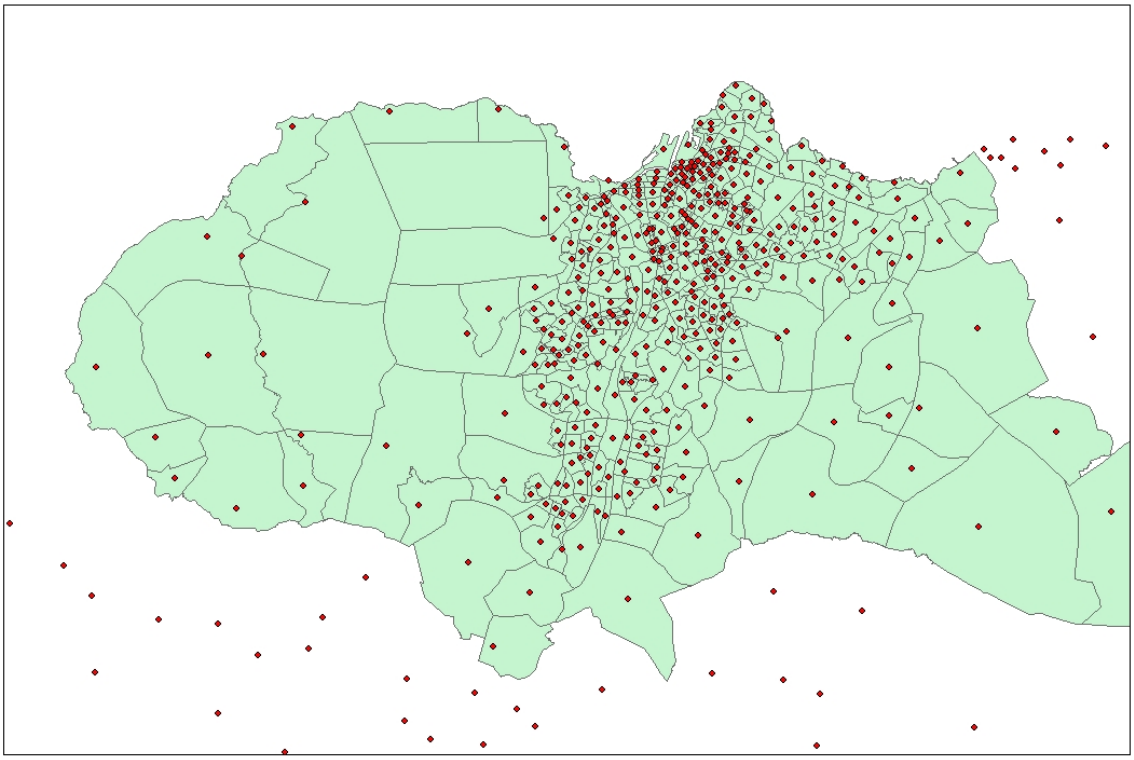
**I Passenger numbers Trondheim buses** in 2009 (supplied by AtB)

| cyear | Linje | PassPrÅr |
|---|---|---|
| 2009 | 4 | 1206139 |
| 2009 | 5 | 3105876 |
| 2009 | 6 | 1002938 |
| 2009 | 7 | 1047446 |
| 2009 | 8 | 1672950 |
| 2009 | 9 | 1795287 |
| 2009 | 10 | 15636 |
| 2009 | 11 | 312485 |
| 2009 | 20 | 313464 |
| 2009 | 36 | 557435 |
| 2009 | 46 | 1142023 |
| 2009 | 52 | 387357 |
| 2009 | 55 | 274754 |
| 2009 | 60 | 401725 |
| 2009 | 63 | 281734 |
| 2009 | 66 | 602507 |
| 2009 | 67 | 2734 |
| 2009 | 80 | 13058 |
| 2009 | 93 | 2773 |
| 2009 | 94 | 4624 |
| 2009 | 95 | 8134 |
| 2009 | 97 | 4368 |
| 2009 | 104 | 364 |
| 2009 | 105 | 389 |
| 2009 | 106 | 398 |
| 2009 | 107 | 266 |
| 2009 | 109 | 247 |
| 2009 | 119 | 182 |
| 2009 | 136 | 462 |
| 2009 | 146 | 283 |
| 2009 | 154 | 130 |
| 2009 | 155 | 424 |
| 2009 | 777 | 6577 |

## II *Sone* attributes

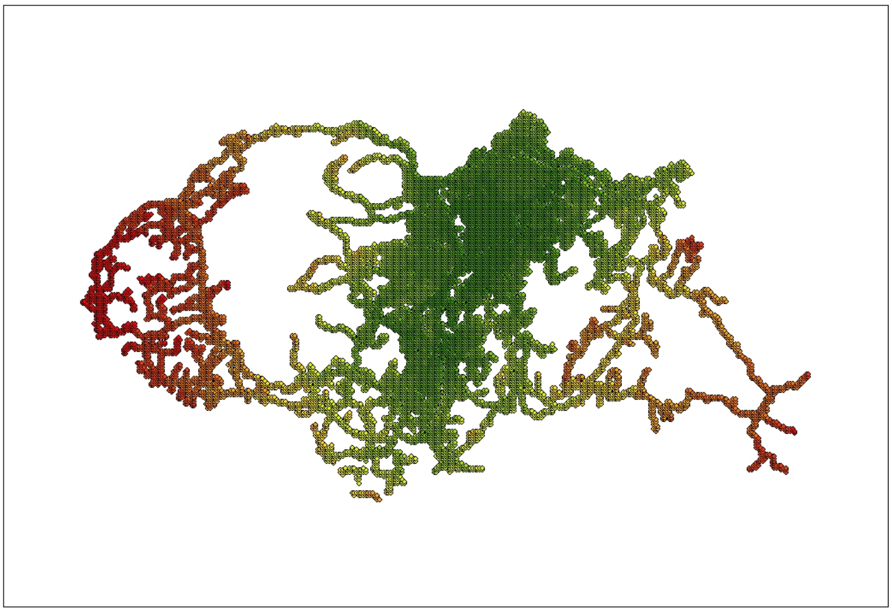
| Sone | Area (sq km) | Residential area - sq km) | Population 2010 |
|---:|---:|---:|---:|
| 0 | 0.56165824 | 0 | 1 |
| 1 | 2.26982917 | 0.66855099 | 3490 |
| 2 | 18.77618214 | 1.082915329 | 2499 |
| 3 | 1.10124669 | 0.609618274 | 3685 |
| 4 | 1.66865491 | 0.732987963 | 3786 |
| 5 | 0.90526664 | 0.716776421 | 2954 |
| 6 | 0.55518676 | 0.476995596 | 5216 |
| 7 | 0.67551393 | 0.630349829 | 3054 |
| 8 | 1.35846445 | 0.582222622 | 5328 |
| 9 | 3.21486949 | 1.29508531 | 5193 |
| 10 | 1.59535304 | 1.180792305 | 4192 |
| 11 | 1.87110883 | 0.897243672 | 3584 |
| 12 | 2.35139309 | 1.054584834 | 3153 |
| 13 | 1.28460555 | 1.009994292 | 3491 |
| 14 | 1.34923566 | 0.506601952 | 2039 |
| 15 | 6.94612206 | 1.879207363 | 4334 |
| 16 | 4.37676834 | 1.140780677 | 3188 |
| 17 | 1.31691515 | 1.137310843 | 3946 |
| 18 | 1.02696854 | 0.812044857 | 4482 |
| 19 | 1.62216842 | 0.93491994 | 3373 |
| 20 | 8.75766159 | 1.697119501 | 4625 |
| 21 | 2.08729651 | 1.180009358 | 4480 |
| 22 | 1.51288135 | 0.812971765 | 2920 |
| 23 | 1.386293 | 1.077239733 | 3264 |
| 24 | 2.89207835 | 0.881515126 | 2522 |
| 25 | 0.76009493 | 0.655643106 | 2810 |
| 26 | 1.4323894 | 0.761568333 | 3820 |
| 27 | 91.35243714 | 3.413441382 | 2221 |
| 28 | 1.83618786 | 1.19189392 | 3064 |
| 29 | 0.64007838 | 0.579916315 | 2812 |
| 30 | 8.54339035 | 0.987622778 | 3344 |
| 31 | 11.28393907 | 2.135523023 | 4283 |
| 32 | 1.39707298 | 1.15164012 | 3317 |
| 33 | 1.45841842 | 0.871107525 | 2703 |
| 34 | 2.16186911 | 1.713006702 | 5401 |
| 35 | 1.61186165 | 1.176050631 | 4564 |
| 36 | 3.97781624 | 1.540330492 | 4914 |
| 37 | 0.74564661 | 0.389314222 | 1754 |
| 38 | 7.06006347 | 1.626826856 | 6929 |
| 39 | 1.08388461 | 0.672017731 | 4734 |
| 40 | 3.14071022 | 1.180277045 | 3213 |
| 41 | 0.88633703 | 0.756720561 | 2402 |
| 42 | 5.0438117 | 1.185489488 | 3042 |
| 43 | 2.36114419 | 0.932755854 | 4163 |
| 44 | 4.29319214 | 1.072990394 | 4532 |
| 45 | 15.09036929 | 1.35473574 | 3437 |
| 46 | 104 | 6.586682388 | 4507 |

## III Grunnkrets centre points

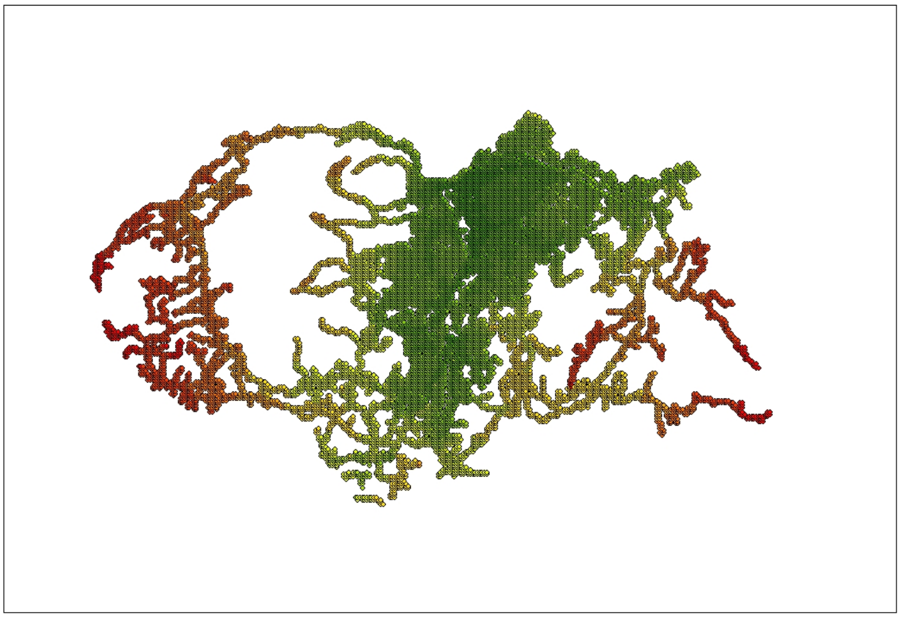


## IV Asplan Viak point grid maps of average travel time to all other points in Trondheim along the network – scale runs from green through yellow to red.

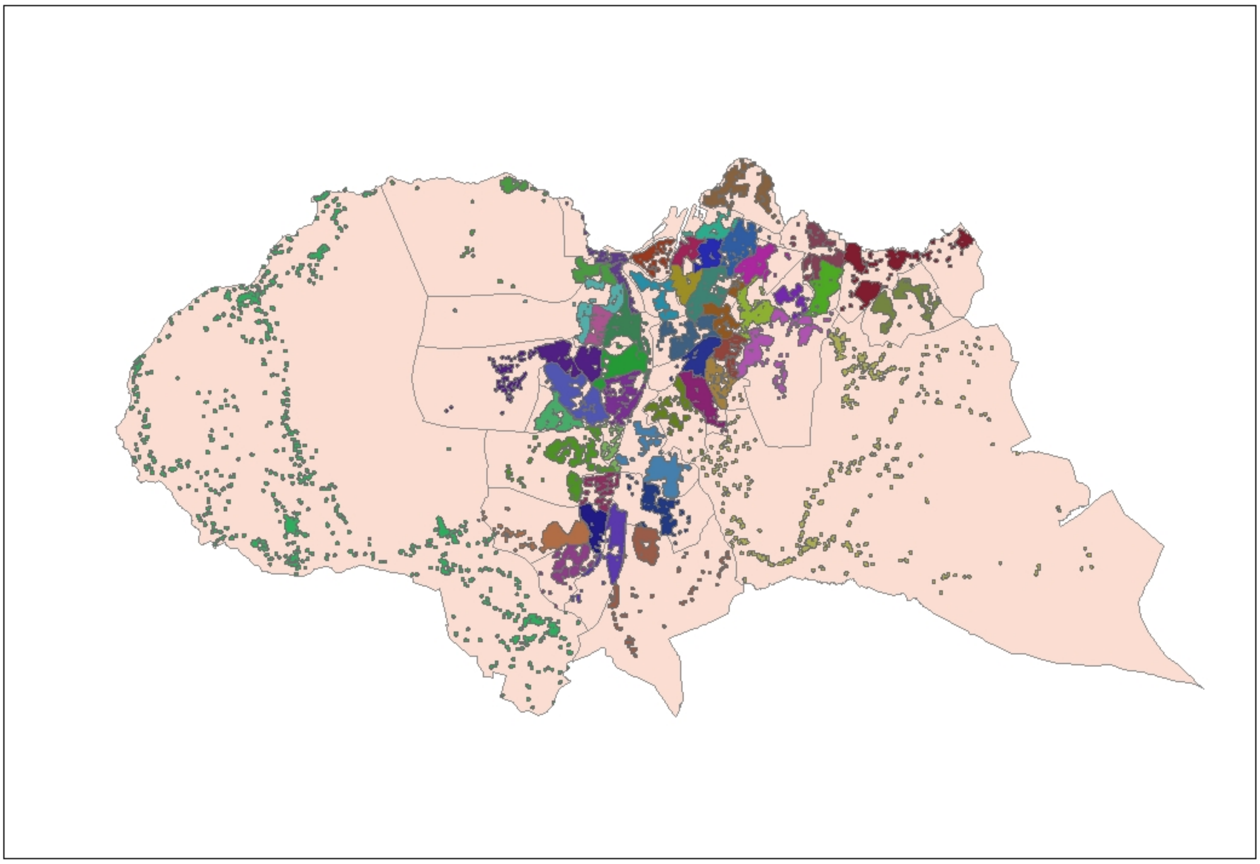
### Car



### Public transport



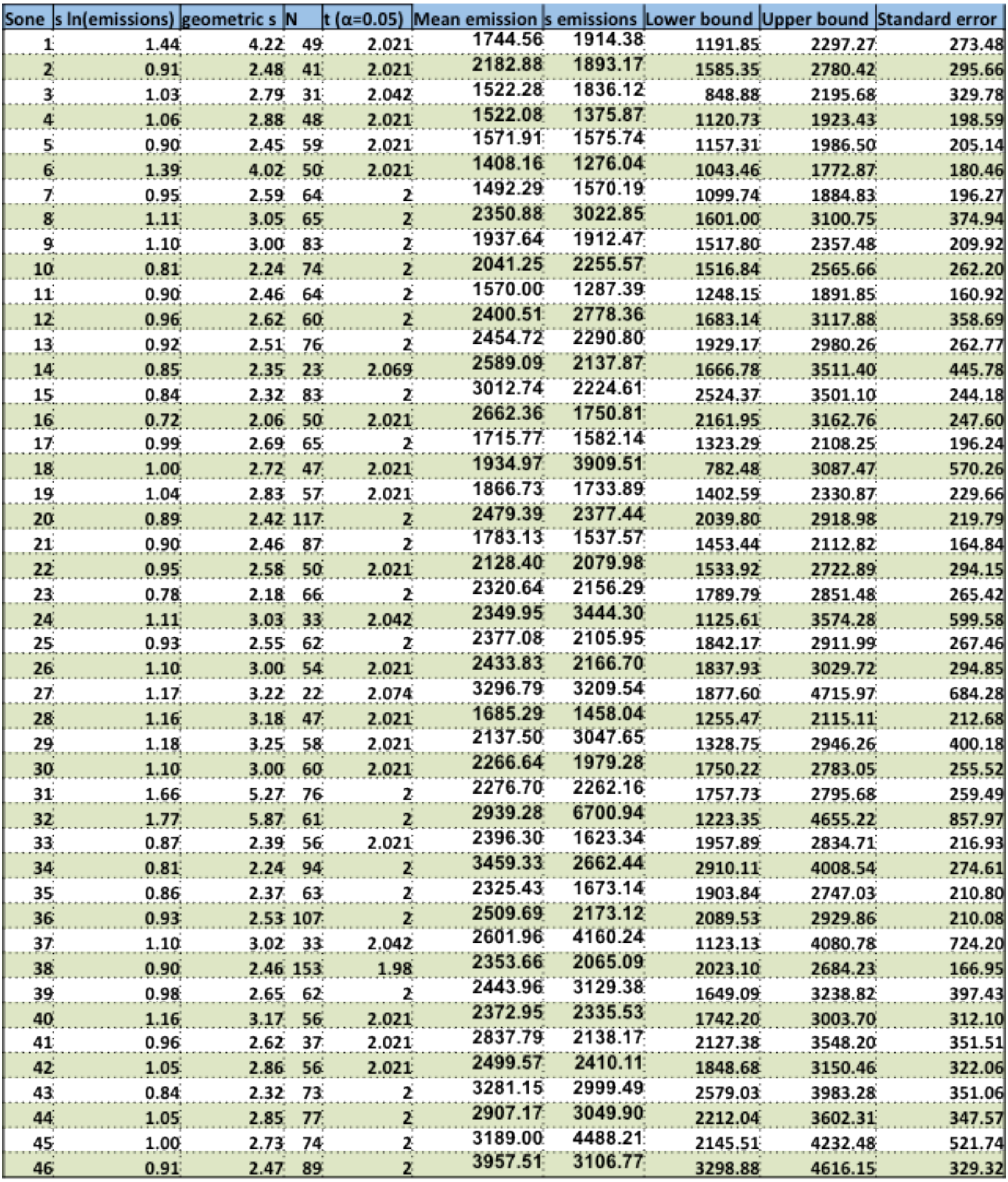
V Residential area in Trondheim based on all area within 50 metres of residental buildings. Soner distinguished by colour.



## VI Population modelling in baseline, centralisation and dispersal scenarios

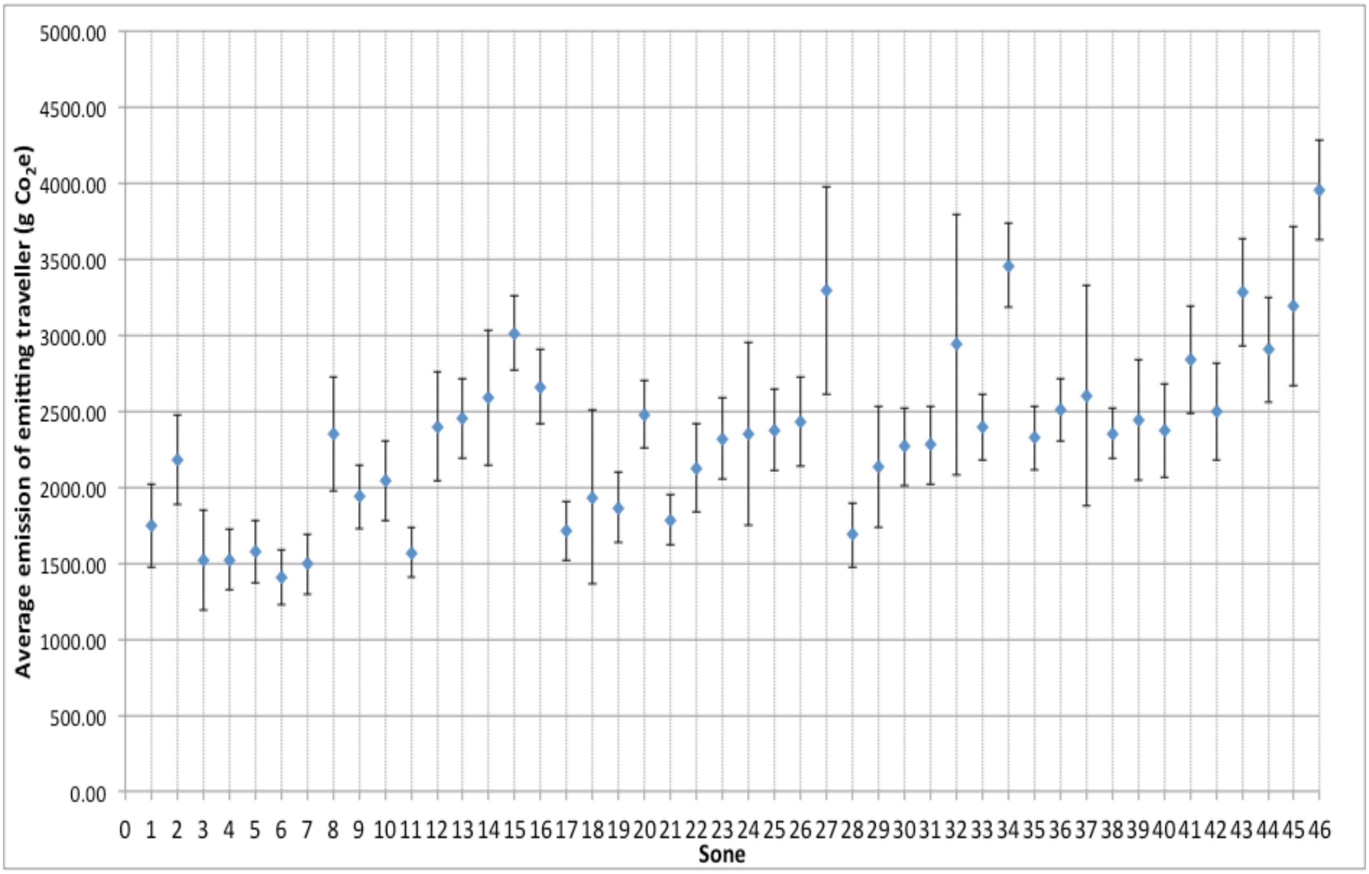
| | Present | Baseline | Centralisation | | Dispersal | |
|---|---|---|---|---|---|---|
| Sone | 2010 | 2030 | Change | 2030 | Change | 2030 |
| 0 | | 0 | 2500 | 2500 | 0 | 0 |
| 1 | 3490 | 4185.892017 | 1000 | 5185.892017 | -700 | 3485.892017 |
| 2 | 2499 | 2769.362285 | | 2769.362285 | 0 | 2769.362285 |
| 3 | 3685 | 4589.161959 | 1000 | 5589.161959 | -900 | 3689.161959 |
| 4 | 3786 | 4470.033181 | 1500 | 5970.033181 | -600 | 3870.033181 |
| 5 | 2954 | 3283.569022 | 1000 | 4283.569022 | -300 | 2983.569022 |
| 6 | 5216 | 5733.513897 | 1000 | 6733.513897 | -500 | 5233.513897 |
| 7 | 3054 | 3421.516979 | 1000 | 4421.516979 | -300 | 3121.516979 |
| 8 | 5328 | 10163.27441 | 2200 | 12363.27441 | -4800 | 5363.274413 |
| 9 | 5193 | 7951.611258 | | 7951.611258 | 0 | 7951.611258 |
| 10 | 4192 | 6560.434001 | | 6560.434001 | -2300 | 4260.434001 |
| 11 | 3584 | 4474.178154 | | 4474.178154 | 0 | 4474.178154 |
| 12 | 3153 | 4067.88401 | | 4067.88401 | 0 | 4067.88401 |
| 13 | 3491 | 3934.678036 | | 3934.678036 | 0 | 3934.678036 |
| 14 | 2039 | 2750.393208 | | 2750.393208 | 0 | 2750.393208 |
| 15 | 4334 | 9251.416721 | -4800 | 4451.416721 | 2000 | 11251.41672 |
| 16 | 3188 | 3466.246467 | | 3466.246467 | 0 | 3466.246467 |
| 17 | 3946 | 5017.865274 | 1000 | 6017.865274 | -1000 | 4017.865274 |
| 18 | 4482 | 5559.110593 | 1000 | 6559.110593 | -1000 | 4559.110593 |
| 19 | 3373 | 4027.935025 | | 4027.935025 | 0 | 4027.935025 |
| 20 | 4625 | 8178.477594 | -3500 | 4678.477594 | 1000 | 9178.477594 |
| 21 | 4480 | 7093.077844 | 1000 | 8093.077844 | -2600 | 4493.077844 |
| 22 | 2920 | 4165.470002 | | 4165.470002 | 0 | 4165.470002 |
| 23 | 3264 | 4482.674795 | | 4482.674795 | 0 | 4482.674795 |
| 24 | 2522 | 3502.580733 | | 3502.580733 | 0 | 3502.580733 |
| 25 | 2810 | 3052.656734 | | 3052.656734 | 0 | 3052.656734 |
| 26 | 3820 | 4693.885536 | | 4693.885536 | 2000 | 6693.885536 |
| 27 | 2221 | 6046.832561 | -3800 | 2246.832561 | 1000 | 7046.832561 |
| 28 | 3064 | 3589.032236 | 1000 | 4589.032236 | -500 | 3089.032236 |
| 29 | 2812 | 3126.249292 | | 3126.249292 | 0 | 3126.249292 |
| 30 | 3344 | 3803.755327 | 1000 | 4803.755327 | -500 | 3303.755327 |
| 31 | 4283 | 4417.653961 | | 4417.653961 | 0 | 4417.653961 |
| 32 | 3317 | 4161.351373 | | 4161.351373 | 0 | 4161.351373 |
| 33 | 2703 | 2625.868448 | | 2625.868448 | 0 | 2625.868448 |
| 34 | 5401 | 5699.560818 | | 5699.560818 | 0 | 5699.560818 |
| 35 | 4564 | 5020.694721 | | 5020.694721 | 0 | 5020.694721 |
| 36 | 4914 | 5349.210177 | | 5349.210177 | 0 | 5349.210177 |
| 37 | 1754 | 1805.325325 | | 1805.325325 | 0 | 1805.325325 |
| 38 | 6929 | 7641.38201 | | 7641.38201 | 1000 | 8641.38201 |
| 39 | 4734 | 5304.922245 | | 5304.922245 | 1000 | 6304.922245 |
| 40 | 3213 | 3469.880029 | | 3469.880029 | 1000 | 4469.880029 |
| 41 | 2402 | 2681.024193 | | 2681.024193 | 1000 | 3681.024193 |
| 42 | 3042 | 3759.05453 | -700 | 3059.05453 | 1000 | 4759.05453 |
| 43 | 4163 | 5086.779887 | -900 | 4186.779887 | 2000 | 7086.779887 |
| 44 | 4532 | 5800.450251 | -1200 | 4600.450251 | 1000 | 6800.450251 |
| 45 | 3437 | 4330.055084 | -800 | 3530.055084 | 1000 | 5330.055084 |
| 46 | 4507 | 5063.014983 | -500 | 4563.014983 | 1000 | 6063.014983 |

**VII Geometric standard deviations and t-statistics for confidence interval estimation on traveller emissions. t- values taken from (Walpole et al. 2012)**



| Sone | s ln(emissions) | geometric s | N | t (α=0.05) | Mean emission | s emissions | Lower bound | Upper bound | Standard error |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.44 | 4.22 | 49 | 2.021 | 1744.56 | 1914.38 | 1191.85 | 2297.27 | 273.48 |
| 2 | 0.91 | 2.48 | 41 | 2.021 | 2182.88 | 1893.17 | 1585.35 | 2780.42 | 295.66 |
| 3 | 1.03 | 2.79 | 31 | 2.042 | 1522.28 | 1836.12 | 848.88 | 2195.68 | 329.78 |
| 4 | 1.06 | 2.88 | 48 | 2.021 | 1522.08 | 1375.87 | 1120.73 | 1923.43 | 198.59 |
| 5 | 0.90 | 2.45 | 59 | 2.021 | 1571.91 | 1575.74 | 1157.31 | 1986.50 | 205.14 |
| 6 | 1.39 | 4.02 | 50 | 2.021 | 1408.16 | 1276.04 | 1043.46 | 1772.87 | 180.46 |
| 7 | 0.95 | 2.59 | 64 | 2 | 1492.29 | 1570.19 | 1099.74 | 1884.83 | 196.27 |
| 8 | 1.11 | 3.05 | 65 | 2 | 2350.88 | 3022.85 | 1601.00 | 3100.75 | 374.94 |
| 9 | 1.10 | 3.00 | 83 | 2 | 1937.64 | 1912.47 | 1517.80 | 2357.48 | 209.92 |
| 10 | 0.81 | 2.24 | 74 | 2 | 2041.25 | 2255.57 | 1516.84 | 2565.66 | 262.20 |
| 11 | 0.90 | 2.46 | 64 | 2 | 1570.00 | 1287.39 | 1248.15 | 1891.85 | 160.92 |
| 12 | 0.96 | 2.62 | 60 | 2 | 2400.51 | 2778.36 | 1683.14 | 3117.88 | 358.69 |
| 13 | 0.92 | 2.51 | 76 | 2 | 2454.72 | 2290.80 | 1929.17 | 2980.26 | 262.77 |
| 14 | 0.85 | 2.35 | 23 | 2.069 | 2589.09 | 2137.87 | 1666.78 | 3511.40 | 445.78 |
| 15 | 0.84 | 2.32 | 83 | 2 | 3012.74 | 2224.61 | 2524.37 | 3501.10 | 244.18 |
| 16 | 0.72 | 2.06 | 50 | 2.021 | 2662.36 | 1750.81 | 2161.95 | 3162.76 | 247.60 |
| 17 | 0.99 | 2.69 | 65 | 2 | 1715.77 | 1582.14 | 1323.29 | 2108.25 | 196.24 |
| 18 | 1.00 | 2.72 | 47 | 2.021 | 1934.97 | 3909.51 | 782.48 | 3087.47 | 570.26 |
| 19 | 1.04 | 2.83 | 57 | 2.021 | 1866.73 | 1733.89 | 1402.59 | 2330.87 | 229.66 |
| 20 | 0.89 | 2.42 | 117 | 2 | 2479.39 | 2377.44 | 2039.80 | 2918.98 | 219.79 |
| 21 | 0.90 | 2.46 | 87 | 2 | 1783.13 | 1537.57 | 1453.44 | 2112.82 | 164.84 |
| 22 | 0.95 | 2.58 | 50 | 2.021 | 2128.40 | 2079.98 | 1533.92 | 2722.89 | 294.15 |
| 23 | 0.78 | 2.18 | 66 | 2 | 2320.64 | 2156.29 | 1789.79 | 2851.48 | 265.42 |
| 24 | 1.11 | 3.03 | 33 | 2.042 | 2349.95 | 3444.30 | 1125.61 | 3574.28 | 599.58 |
| 25 | 0.93 | 2.55 | 62 | 2 | 2377.08 | 2105.95 | 1842.17 | 2911.99 | 267.46 |
| 26 | 1.10 | 3.00 | 54 | 2.021 | 2433.83 | 2166.70 | 1837.93 | 3029.72 | 294.85 |
| 27 | 1.17 | 3.22 | 22 | 2.074 | 3296.79 | 3209.54 | 1877.60 | 4715.97 | 684.28 |
| 28 | 1.16 | 3.18 | 47 | 2.021 | 1685.29 | 1458.04 | 1255.47 | 2115.11 | 212.68 |
| 29 | 1.18 | 3.25 | 58 | 2.021 | 2137.50 | 3047.65 | 1328.75 | 2946.26 | 400.18 |
| 30 | 1.10 | 3.00 | 60 | 2.021 | 2266.64 | 1979.28 | 1750.22 | 2783.05 | 255.52 |
| 31 | 1.66 | 5.27 | 76 | 2 | 2276.70 | 2262.16 | 1757.73 | 2795.68 | 259.49 |
| 32 | 1.77 | 5.87 | 61 | 2 | 2939.28 | 6700.94 | 1223.35 | 4655.22 | 857.97 |
| 33 | 0.87 | 2.39 | 56 | 2.021 | 2396.30 | 1623.34 | 1957.89 | 2834.71 | 216.93 |
| 34 | 0.81 | 2.24 | 94 | 2 | 3459.33 | 2662.44 | 2910.11 | 4008.54 | 274.61 |
| 35 | 0.86 | 2.37 | 63 | 2 | 2325.43 | 1673.14 | 1903.84 | 2747.03 | 210.80 |
| 36 | 0.93 | 2.53 | 107 | 2 | 2509.69 | 2173.12 | 2089.53 | 2929.86 | 210.08 |
| 37 | 1.10 | 3.02 | 33 | 2.042 | 2601.96 | 4160.24 | 1123.13 | 4080.78 | 724.20 |
| 38 | 0.90 | 2.46 | 153 | 1.98 | 2353.66 | 2065.09 | 2023.10 | 2684.23 | 166.95 |
| 39 | 0.98 | 2.65 | 62 | 2 | 2443.96 | 3129.38 | 1649.09 | 3238.82 | 397.43 |
| 40 | 1.16 | 3.17 | 56 | 2.021 | 2372.95 | 2335.53 | 1742.20 | 3003.70 | 312.10 |
| 41 | 0.96 | 2.62 | 37 | 2.021 | 2837.79 | 2138.17 | 2127.38 | 3548.20 | 351.51 |
| 42 | 1.05 | 2.86 | 56 | 2.021 | 2499.57 | 2410.11 | 1848.68 | 3150.46 | 322.06 |
| 43 | 0.84 | 2.32 | 73 | 2 | 3281.15 | 2999.49 | 2579.03 | 3983.28 | 351.06 |
| 44 | 1.05 | 2.85 | 77 | 2 | 2907.17 | 3049.90 | 2212.04 | 3602.31 | 347.57 |
| 45 | 1.00 | 2.73 | 74 | 2 | 3189.00 | 4488.21 | 2145.51 | 4232.48 | 521.74 |
| 46 | 0.91 | 2.47 | 89 | 2 | 3957.51 | 3106.77 | 3298.88 | 4616.15 | 329.32 |

**VIII Confidence intervals for emitting travellers using t-statistic method** (after (Armstrong 1992)



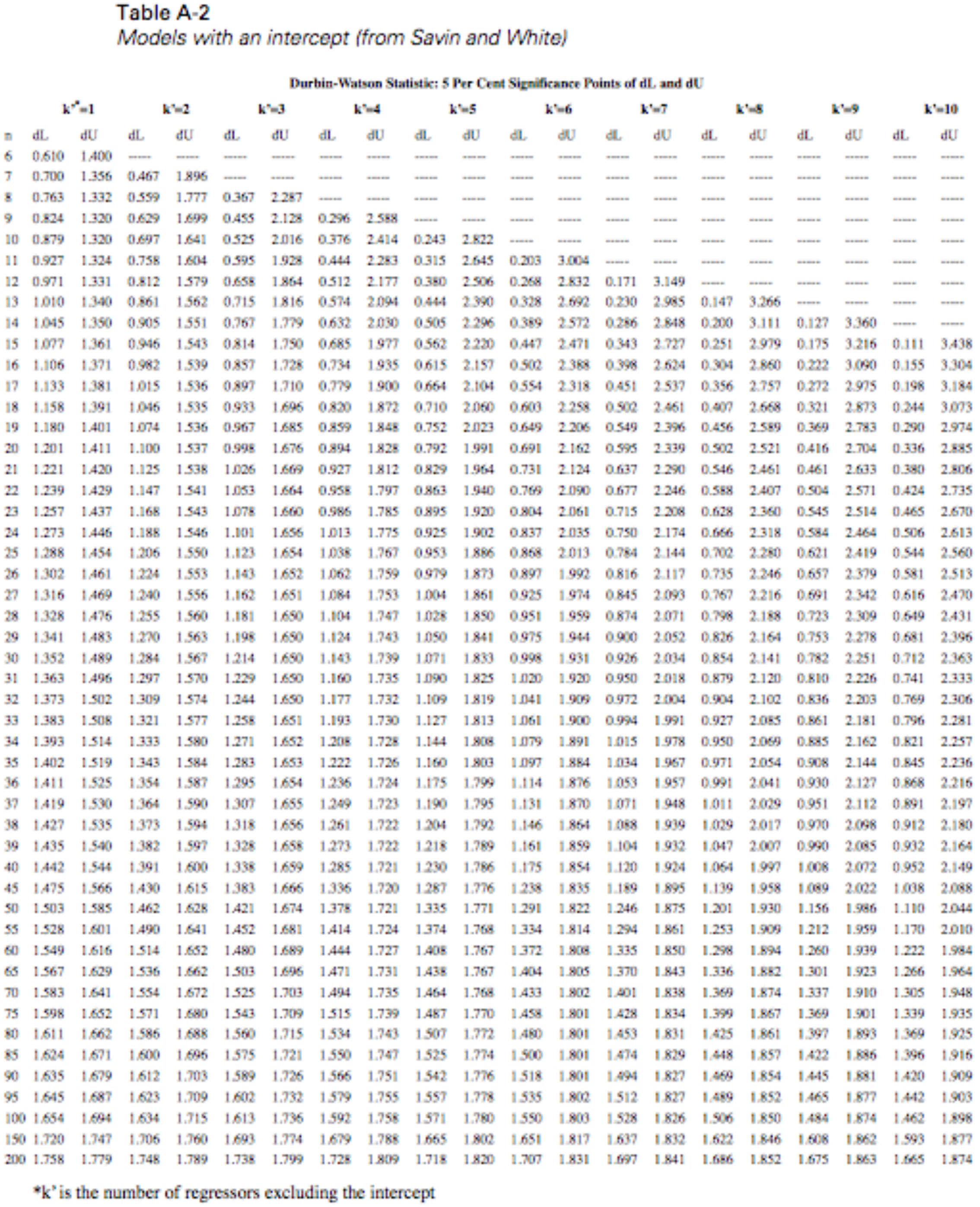
## IX Exploratory regression results from ArcMap

Criteria for passing models are shown below

```
Choose 1 of 7 Summary
    Highest Adjusted R-Squared Results
  R2   AICc  JB  BP  VIF  MI  Model
0.75 647.59 0.04 0.81 1.00 0.14  +SHEET1$.CDIS***
0.52 677.18 0.00 0.25 1.00 0.66  +SHEET1$.UND16***
0.50 678.77 0.42 0.82 1.00 0.00  +SHEET1$.TRANS2***
                  Passing Models
R2      AICc      JB      BP      VIF      MI        Model
0.746645 647.586690 0.044710 0.808045 1.000000 0.136239  +SHEET1$.CDIS***

*******************************************************************************
Choose 2 of 7 Summary
         Highest Adjusted R-Squared Results
  R2   AICc  JB  BP  VIF  MI  Model
0.78 641.44 0.01 0.87 1.36 0.74  +SHEET1$.CDIS***  -SHEET1$.PDEN***
0.77 643.58 0.16 0.66 1.90 0.82  +SHEET1$.CDIS***  +SHEET1$.UND16**
0.77 644.55 0.00 0.90 1.89 0.39  +SHEET1$.CDIS***  +SHEET1$.TRANS2**
                         Passing Models
R2      AICc      JB      BP      VIF      MI        Model
0.774485 643.578650 0.161028 0.664782 1.899084 0.824577  +SHEET1$.CDIS***  +SHEET1$.UND16**
0.764138 645.642211 0.042622 0.807233 1.553999 0.416121  +SHEET1$.CDIS***  +SHEET1$.CAR**
0.749509 648.410291 0.074043 0.647683 1.201238 0.209366  +SHEET1$.CDIS***  +SHEET1$.INC
0.677248 660.069630 0.627907 0.644166 1.342219 0.185262  +SHEET1$.TRANS2***  +SHEET1$.UND16***
0.596637 670.325405 0.503779 0.689552 1.342543 0.012818  +SHEET1$.TRANS2***  +SHEET1$.CAR***
0.552877 675.063225 0.350699 0.072402 1.974325 0.860077  -SHEET1$.RDEN  +SHEET1$.UND16***
0.526161 677.732795 0.056077 0.188654 2.100220 0.926566  -SHEET1$.PDEN  +SHEET1$.UND16***
0.508669 679.400351 0.522161 0.445109 1.533620 0.150187  -SHEET1$.RDEN***  +SHEET1$.CAR***

*******************************************************************************
Choose 3 of 7 Summary
               Highest Adjusted R-Squared Results
  R2   AICc  JB  BP  VIF  MI  Model
0.79 640.65 0.01 0.79 2.68 0.98  +SHEET1$.CDIS***  +SHEET1$.TRANS2**  +SHEET1$.UND16**
0.79 642.53 0.00 0.79 2.41 0.75  +SHEET1$.CDIS***  -SHEET1$.PDEN**  +SHEET1$.TRANS2
0.79 642.81 0.04 0.91 2.94 0.98  +SHEET1$.CDIS***  -SHEET1$.PDEN*  +SHEET1$.UND16
                              Passing Models
R2      AICc      JB      BP      VIF      MI        Model
0.794931 640.648843 0.014108 0.788195 2.679708 0.975887  +SHEET1$.CDIS***  +SHEET1$.TRANS2**  +SHEET1$.UND16**
0.775175 644.879797 0.070420 0.844268 2.472983 0.997952  +SHEET1$.CDIS***  -SHEET1$.RDEN  +SHEET1$.UND16*
0.682916 660.696616 0.569747 0.344346 3.180504 0.120452  +SHEET1$.TRANS2***  -SHEET1$.INC  +SHEET1$.UND16***
0.598406 671.565233 0.459596 0.941837 2.348436 0.019297  -SHEET1$.RDEN  +SHEET1$.TRANS2***  +SHEET1$.CAR***
0.569966 674.712661 0.108484 0.124003 3.868723 0.806183  -SHEET1$.RDEN*  -SHEET1$.INC  +SHEET1$.UND16***
0.566177 675.116179 0.027956 0.379238 3.180783 0.830506  -SHEET1$.PDEN*  -SHEET1$.INC**  +SHEET1$.UND16***
0.521349 679.639538 0.274562 0.682943 3.867361 0.128520  -SHEET1$.RDEN***  -SHEET1$.INC  +SHEET1$.CAR***

*******************************************************************************
```

```
Choose 4 of 7 Summary
                    Highest Adjusted R-Squared Results
 R2   AICc   JB   BP  VIF   MI   Model
0.79 642.71 0.01 0.87 4.22 0.93  +SHEET1$.CDIS***  +SHEET1$.TRANS2**  -SHEET1$.INC  +SHEET1$.UND16**
0.79 642.79 0.01 0.89 3.24 0.98  +SHEET1$.CDIS***  -SHEET1$.PDEN  +SHEET1$.TRANS2  +SHEET1$.UND16
0.79 643.27 0.02 0.89 4.74 0.94  +SHEET1$.CDIS***  +SHEET1$.TRANS2**  -SHEET1$.CAR  +SHEET1$.UND16*
                                   Passing Models
R2       AICc       JB       BP       VIF      MI        Model
0.787937 643.736793 0.026197 0.948166 4.735713 0.999354  +SHEET1$.CDIS***  -SHEET1$.PDEN*  -SHEET1$.INC  +SHEET1$.UND16
0.579851 675.188330 0.065610 0.583420 5.264671 0.796458  -SHEET1$.RDEN*  -SHEET1$.INC**  +SHEET1$.CAR  +SHEET1$.UND16**
0.571379 676.106624 0.225905 0.191889 4.006542 0.574700  -SHEET1$.PDEN  -SHEET1$.RDEN  -SHEET1$.INC*  +SHEET1$.UND16***
0.567734 676.496189 0.014697 0.702137 5.595434 0.757487  -SHEET1$.PDEN  -SHEET1$.INC**  +SHEET1$.CAR  +SHEET1$.UND16***

********************************************************************************
Choose 5 of 7 Summary
                         Highest Adjusted R-Squared Results
 R2   AICc   JB   BP  VIF   MI   Model
0.79 644.56 0.01 0.94 4.81 0.96  +SHEET1$.CDIS***  -SHEET1$.PDEN  +SHEET1$.TRANS2  -SHEET1$.INC  +SHEET1$.UND16*
0.79 645.41 0.01 0.95 5.84 0.98  +SHEET1$.CDIS***  +SHEET1$.TRANS2**  -SHEET1$.INC  +SHEET1$.CAR  +SHEET1$.UND16*
0.79 645.46 0.01 0.94 5.33 0.95  +SHEET1$.CDIS***  -SHEET1$.PDEN  +SHEET1$.TRANS2  -SHEET1$.CAR  +SHEET1$.UND16
   Passing Models
R2 AICc JB BP VIF MI   Model

********************************************************************************
*********** Exploratory Regression Global Summary (SHEET1$.Y3ADJ2) ***********

      Percentage of Search Criteria Passed
     Search Criterion Cutoff Trials # Passed % Passed
 Min Adjusted R-Squared > 0.50    119      108    90.76
Max Coefficient p-value < 0.30    119       46    38.66
        Max VIF Value < 7.50    119      119   100.00
Min Jarque-Bera p-value > 0.01    119       85    71.43
 Min Moran's I p-value > 0.01     35       31    88.57

--------------------------------------------------------------------------------
```

## X Durbin Watson table (Savin & White 1977)



### Table A-2

*Models with an intercept (from Savin and White)*

**Durbin-Watson Statistic: 5 Per Cent Significance Points of dL and dU**

| | k'*=1 | | k'=2 | | k'=3 | | k'=4 | | k'=5 | | k'=6 | | k'=7 | | k'=8 | | k'=9 | | k'=10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| n | dL | dU | dL | dU | dL | dU | dL | dU | dL | dU | dL | dU | dL | dU | dL | dU | dL | dU | dL | dU |
| 6 | 0.610 | 1.400 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 7 | 0.700 | 1.356 | 0.467 | 1.896 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 8 | 0.763 | 1.332 | 0.559 | 1.777 | 0.367 | 2.287 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 9 | 0.824 | 1.320 | 0.629 | 1.699 | 0.455 | 2.128 | 0.296 | 2.588 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 10 | 0.879 | 1.320 | 0.697 | 1.641 | 0.525 | 2.016 | 0.376 | 2.414 | 0.243 | 2.822 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 11 | 0.927 | 1.324 | 0.758 | 1.604 | 0.595 | 1.928 | 0.444 | 2.283 | 0.315 | 2.645 | 0.203 | 3.004 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 12 | 0.971 | 1.331 | 0.812 | 1.579 | 0.658 | 1.864 | 0.512 | 2.177 | 0.380 | 2.506 | 0.268 | 2.832 | 0.171 | 3.149 | ----- | ----- | ----- | ----- | ----- | ----- |
| 13 | 1.010 | 1.340 | 0.861 | 1.562 | 0.715 | 1.816 | 0.574 | 2.094 | 0.444 | 2.390 | 0.328 | 2.692 | 0.230 | 2.985 | 0.147 | 3.266 | ----- | ----- | ----- | ----- |
| 14 | 1.045 | 1.350 | 0.905 | 1.551 | 0.767 | 1.779 | 0.632 | 2.030 | 0.505 | 2.296 | 0.389 | 2.572 | 0.286 | 2.848 | 0.200 | 3.111 | 0.127 | 3.360 | ----- | ----- |
| 15 | 1.077 | 1.361 | 0.946 | 1.543 | 0.814 | 1.750 | 0.685 | 1.977 | 0.562 | 2.220 | 0.447 | 2.471 | 0.343 | 2.727 | 0.251 | 2.979 | 0.175 | 3.216 | 0.111 | 3.438 |
| 16 | 1.106 | 1.371 | 0.982 | 1.539 | 0.857 | 1.728 | 0.734 | 1.935 | 0.615 | 2.157 | 0.502 | 2.388 | 0.398 | 2.624 | 0.304 | 2.860 | 0.222 | 3.090 | 0.155 | 3.304 |
| 17 | 1.133 | 1.381 | 1.015 | 1.536 | 0.897 | 1.710 | 0.779 | 1.900 | 0.664 | 2.104 | 0.554 | 2.318 | 0.451 | 2.537 | 0.356 | 2.757 | 0.272 | 2.975 | 0.198 | 3.184 |
| 18 | 1.158 | 1.391 | 1.046 | 1.535 | 0.933 | 1.696 | 0.820 | 1.872 | 0.710 | 2.060 | 0.603 | 2.258 | 0.502 | 2.461 | 0.407 | 2.668 | 0.321 | 2.873 | 0.244 | 3.073 |
| 19 | 1.180 | 1.401 | 1.074 | 1.536 | 0.967 | 1.685 | 0.859 | 1.848 | 0.752 | 2.023 | 0.649 | 2.206 | 0.549 | 2.396 | 0.456 | 2.589 | 0.369 | 2.783 | 0.290 | 2.974 |
| 20 | 1.201 | 1.411 | 1.100 | 1.537 | 0.998 | 1.676 | 0.894 | 1.828 | 0.792 | 1.991 | 0.691 | 2.162 | 0.595 | 2.339 | 0.502 | 2.521 | 0.416 | 2.704 | 0.336 | 2.885 |
| 21 | 1.221 | 1.420 | 1.125 | 1.538 | 1.026 | 1.669 | 0.927 | 1.812 | 0.829 | 1.964 | 0.731 | 2.124 | 0.637 | 2.290 | 0.546 | 2.461 | 0.461 | 2.633 | 0.380 | 2.806 |
| 22 | 1.239 | 1.429 | 1.147 | 1.541 | 1.053 | 1.664 | 0.958 | 1.797 | 0.863 | 1.940 | 0.769 | 2.090 | 0.677 | 2.246 | 0.588 | 2.407 | 0.504 | 2.571 | 0.424 | 2.735 |
| 23 | 1.257 | 1.437 | 1.168 | 1.543 | 1.078 | 1.660 | 0.986 | 1.785 | 0.895 | 1.920 | 0.804 | 2.061 | 0.715 | 2.208 | 0.628 | 2.360 | 0.545 | 2.514 | 0.465 | 2.670 |
| 24 | 1.273 | 1.446 | 1.188 | 1.546 | 1.101 | 1.656 | 1.013 | 1.775 | 0.925 | 1.902 | 0.837 | 2.035 | 0.750 | 2.174 | 0.666 | 2.318 | 0.584 | 2.464 | 0.506 | 2.613 |
| 25 | 1.288 | 1.454 | 1.206 | 1.550 | 1.123 | 1.654 | 1.038 | 1.767 | 0.953 | 1.886 | 0.868 | 2.013 | 0.784 | 2.144 | 0.702 | 2.280 | 0.621 | 2.419 | 0.544 | 2.560 |
| 26 | 1.302 | 1.461 | 1.224 | 1.553 | 1.143 | 1.652 | 1.062 | 1.759 | 0.979 | 1.873 | 0.897 | 1.992 | 0.816 | 2.117 | 0.735 | 2.246 | 0.657 | 2.379 | 0.581 | 2.513 |
| 27 | 1.316 | 1.469 | 1.240 | 1.556 | 1.162 | 1.651 | 1.084 | 1.753 | 1.004 | 1.861 | 0.925 | 1.974 | 0.845 | 2.093 | 0.767 | 2.216 | 0.691 | 2.342 | 0.616 | 2.470 |
| 28 | 1.328 | 1.476 | 1.255 | 1.560 | 1.181 | 1.650 | 1.104 | 1.747 | 1.028 | 1.850 | 0.951 | 1.959 | 0.874 | 2.071 | 0.798 | 2.188 | 0.723 | 2.309 | 0.649 | 2.431 |
| 29 | 1.341 | 1.483 | 1.270 | 1.563 | 1.198 | 1.650 | 1.124 | 1.743 | 1.050 | 1.841 | 0.975 | 1.944 | 0.900 | 2.052 | 0.826 | 2.164 | 0.753 | 2.278 | 0.681 | 2.396 |
| 30 | 1.352 | 1.489 | 1.284 | 1.567 | 1.214 | 1.650 | 1.143 | 1.739 | 1.071 | 1.833 | 0.998 | 1.931 | 0.926 | 2.034 | 0.854 | 2.141 | 0.782 | 2.251 | 0.712 | 2.363 |
| 31 | 1.363 | 1.496 | 1.297 | 1.570 | 1.229 | 1.650 | 1.160 | 1.735 | 1.090 | 1.825 | 1.020 | 1.920 | 0.950 | 2.018 | 0.879 | 2.120 | 0.810 | 2.226 | 0.741 | 2.333 |
| 32 | 1.373 | 1.502 | 1.309 | 1.574 | 1.244 | 1.650 | 1.177 | 1.732 | 1.109 | 1.819 | 1.041 | 1.909 | 0.972 | 2.004 | 0.904 | 2.102 | 0.836 | 2.203 | 0.769 | 2.306 |
| 33 | 1.383 | 1.508 | 1.321 | 1.577 | 1.258 | 1.651 | 1.193 | 1.730 | 1.127 | 1.813 | 1.061 | 1.900 | 0.994 | 1.991 | 0.927 | 2.085 | 0.861 | 2.181 | 0.796 | 2.281 |
| 34 | 1.393 | 1.514 | 1.333 | 1.580 | 1.271 | 1.652 | 1.208 | 1.728 | 1.144 | 1.808 | 1.079 | 1.891 | 1.015 | 1.978 | 0.950 | 2.069 | 0.885 | 2.162 | 0.821 | 2.257 |
| 35 | 1.402 | 1.519 | 1.343 | 1.584 | 1.283 | 1.653 | 1.222 | 1.726 | 1.160 | 1.803 | 1.097 | 1.884 | 1.034 | 1.967 | 0.971 | 2.054 | 0.908 | 2.144 | 0.845 | 2.236 |
| 36 | 1.411 | 1.525 | 1.354 | 1.587 | 1.295 | 1.654 | 1.236 | 1.724 | 1.175 | 1.799 | 1.114 | 1.876 | 1.053 | 1.957 | 0.991 | 2.041 | 0.930 | 2.127 | 0.868 | 2.216 |
| 37 | 1.419 | 1.530 | 1.364 | 1.590 | 1.307 | 1.655 | 1.249 | 1.723 | 1.190 | 1.795 | 1.131 | 1.870 | 1.071 | 1.948 | 1.011 | 2.029 | 0.951 | 2.112 | 0.891 | 2.197 |
| 38 | 1.427 | 1.535 | 1.373 | 1.594 | 1.318 | 1.656 | 1.261 | 1.722 | 1.204 | 1.792 | 1.146 | 1.864 | 1.088 | 1.939 | 1.029 | 2.017 | 0.970 | 2.098 | 0.912 | 2.180 |
| 39 | 1.435 | 1.540 | 1.382 | 1.597 | 1.328 | 1.658 | 1.273 | 1.722 | 1.218 | 1.789 | 1.161 | 1.859 | 1.104 | 1.932 | 1.047 | 2.007 | 0.990 | 2.085 | 0.932 | 2.164 |
| 40 | 1.442 | 1.544 | 1.391 | 1.600 | 1.338 | 1.659 | 1.285 | 1.721 | 1.230 | 1.786 | 1.175 | 1.854 | 1.120 | 1.924 | 1.064 | 1.997 | 1.008 | 2.072 | 0.952 | 2.149 |
| 45 | 1.475 | 1.566 | 1.430 | 1.615 | 1.383 | 1.666 | 1.336 | 1.720 | 1.287 | 1.776 | 1.238 | 1.835 | 1.189 | 1.895 | 1.139 | 1.958 | 1.089 | 2.022 | 1.038 | 2.088 |
| 50 | 1.503 | 1.585 | 1.462 | 1.628 | 1.421 | 1.674 | 1.378 | 1.721 | 1.335 | 1.771 | 1.291 | 1.822 | 1.246 | 1.875 | 1.201 | 1.930 | 1.156 | 1.986 | 1.110 | 2.044 |
| 55 | 1.528 | 1.601 | 1.490 | 1.641 | 1.452 | 1.681 | 1.414 | 1.724 | 1.374 | 1.768 | 1.334 | 1.814 | 1.294 | 1.861 | 1.253 | 1.909 | 1.212 | 1.959 | 1.170 | 2.010 |
| 60 | 1.549 | 1.616 | 1.514 | 1.652 | 1.480 | 1.689 | 1.444 | 1.727 | 1.408 | 1.767 | 1.372 | 1.808 | 1.335 | 1.850 | 1.298 | 1.894 | 1.260 | 1.939 | 1.222 | 1.984 |
| 65 | 1.567 | 1.629 | 1.536 | 1.662 | 1.503 | 1.696 | 1.471 | 1.731 | 1.438 | 1.767 | 1.404 | 1.805 | 1.370 | 1.843 | 1.336 | 1.882 | 1.301 | 1.923 | 1.266 | 1.964 |
| 70 | 1.583 | 1.641 | 1.554 | 1.672 | 1.525 | 1.703 | 1.494 | 1.735 | 1.464 | 1.768 | 1.433 | 1.802 | 1.401 | 1.838 | 1.369 | 1.874 | 1.337 | 1.910 | 1.305 | 1.948 |
| 75 | 1.598 | 1.652 | 1.571 | 1.680 | 1.543 | 1.709 | 1.515 | 1.739 | 1.487 | 1.770 | 1.458 | 1.801 | 1.428 | 1.834 | 1.399 | 1.867 | 1.369 | 1.901 | 1.339 | 1.935 |
| 80 | 1.611 | 1.662 | 1.586 | 1.688 | 1.560 | 1.715 | 1.534 | 1.743 | 1.507 | 1.772 | 1.480 | 1.801 | 1.453 | 1.831 | 1.425 | 1.861 | 1.397 | 1.893 | 1.369 | 1.925 |
| 85 | 1.624 | 1.671 | 1.600 | 1.696 | 1.575 | 1.721 | 1.550 | 1.747 | 1.525 | 1.774 | 1.500 | 1.801 | 1.474 | 1.829 | 1.448 | 1.857 | 1.422 | 1.886 | 1.396 | 1.916 |
| 90 | 1.635 | 1.679 | 1.612 | 1.703 | 1.589 | 1.726 | 1.566 | 1.751 | 1.542 | 1.776 | 1.518 | 1.801 | 1.494 | 1.827 | 1.469 | 1.854 | 1.445 | 1.881 | 1.420 | 1.909 |
| 95 | 1.645 | 1.687 | 1.623 | 1.709 | 1.602 | 1.732 | 1.579 | 1.755 | 1.557 | 1.778 | 1.535 | 1.802 | 1.512 | 1.827 | 1.489 | 1.852 | 1.465 | 1.877 | 1.442 | 1.903 |
| 100 | 1.654 | 1.694 | 1.634 | 1.715 | 1.613 | 1.736 | 1.592 | 1.758 | 1.571 | 1.780 | 1.550 | 1.803 | 1.528 | 1.826 | 1.506 | 1.850 | 1.484 | 1.874 | 1.462 | 1.898 |
| 150 | 1.720 | 1.747 | 1.706 | 1.760 | 1.693 | 1.774 | 1.679 | 1.788 | 1.665 | 1.802 | 1.651 | 1.817 | 1.637 | 1.832 | 1.622 | 1.846 | 1.608 | 1.862 | 1.593 | 1.877 |
| 200 | 1.758 | 1.779 | 1.748 | 1.789 | 1.738 | 1.799 | 1.728 | 1.809 | 1.718 | 1.820 | 1.707 | 1.831 | 1.697 | 1.841 | 1.686 | 1.852 | 1.675 | 1.863 | 1.665 | 1.874 |

*k' is the number of regressors excluding the intercept

**XI Emissions curves for *delområde* in Trondheim** presented in distance from centre order (l-r) – note the reduction in zero-emitters and the change in the shape of the lognormal-type curve with distance.