ASSESSING CLIMATE VALUE OF CYCLING UNDER DIFFERENT URBAN FORMS OF DUTCH CITIES

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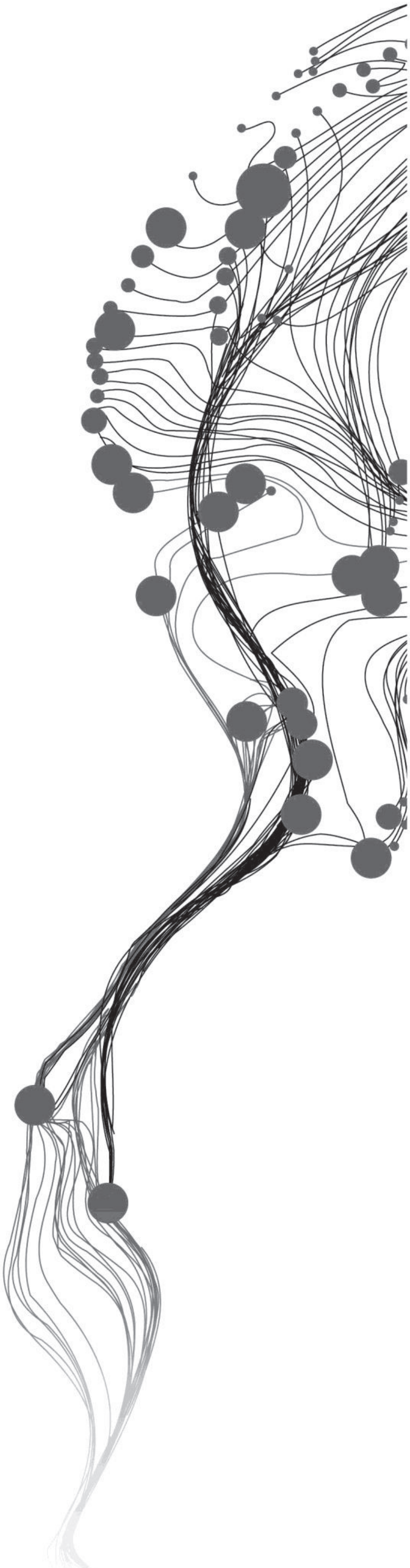

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ABSTRACT

Cycling as a clean (non-emission) transport mode receives little attention in the scientific literature in terms of its climate mitigation potential. The Climate Value of Cycling (CVoC) represents the total amounts of avoided emissions due to cycling and is derived from an estimation of the total number of cycling trips, and their most likely substitution mode albeit motorized or non-motorized based on information about the current trip characteristics. Since urban form factors are reported to influence travel behaviour and patterns worldwide, also for cycling, there exists a link between the CVoC and urban form. This research quantifies the CVoC for Dutch cities—not only because The Netherlands has a reputation in facilitating and encouraging cycling and achieved great success in terms of its large cycling share, but also due to a lack of systematic and nationwide assessment of cycling from a climate perspective. The CVoC for Dutch cities is shown to correlate with important urban form indicators. Associative relations are tested in this research to quantify the extent to which urban form is related to the level of sustainability of the transport system. The results provide recommendations on the planning of sustainable urban form and transport geared towards mitigating climate emissions.

ACKNOWLEGEMENTS

I came to the Netherlands to study urban planning, with a bit of Dutch flavour. And now I have fulfilled this goal with fruits.
I have been recalling the two hours when Mark Zuidgeest introduced me the national transport survey report, which is written in Dutch, translated each important term into English on the paper and discussed with me what would raise my interest of research. I also remember the moment when he "hacked" into Professor Martin van Maarseveen's room to get the book which introduces basic Matlab knowledge for me. I hereby express my sincere thanks to him for his enlightenment on my research and patience of my progress. My special thanks also go to Mark Brussel, with whom we started to discuss the primitive maps that I produced and succeeded in turning my first stage outputs into an ETC conference paper with our joint efforts. I appreciate all the meetings we three had and the hundreds of e-mails we wrote for communication, which make my research clearer and clearer. I would also grant my gratitude to Professor Martin van Maarseveen, who corrected my direction of conducting my research at the very crucial moment. I am also grateful to Ir. Frans van den Bosch and Ir. Roel Massink, without whose provision of data and introduction of his Matlab scripts my research would be impossible to carry out.
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My knowledge of the world is and will never be complete, and I am happy about it.

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1. INTRODUCTION

1.1. Introduction and background

Cycling is an established tradition in The Netherlands as a utilitarian transport mode (Pucher & Buehler, 2008). It helps to reduce the carbon footprint of urban transport. But it is threatened by the increasing use of cars which support the accessibility and mobility of people who tend to enjoy a suburban lifestyle, which in the long term would create dispersed land use not suitable for cycling. Without understanding the interaction between land use and transport and its impact on climate change, planners are less prepared for sustainable urban development.

1.1.1. A world with rapid urbanization facing the challenge of sustainable development

Urbanization has been a predominant process all over the world in the past decades. More and more people are living in cities. The urban population of the world quadrupled in 2000 since the 1950s. With rapid urbanization, cities are reshaped; their citizens are confronted with different kinds of problems and their authorities are facing many challenges. While developments are bringing economic increase and technological renovation, they are also creating problems, especially when such developments are at the expense of our environment.

Sustainable strategies are required, on the one hand to guide the urban growth and maintain economic development, and on the other hand to alleviate problems brought by urbanization and improper development. Planning sustainable urban areas is of essential importance for urban planners nowadays. The bicycle plays a very important role in sustainable urban development, especially from the perspective if its ability in mitigating climate change.

1.1.2. Automobile-driven development, suburbanization and urban sprawl

Many rural areas of the planet earth have been urbanized due to the increasing use and dependency on private vehicles. This is especially true for the United States in the late 20th century. Nowadays many cities are following such automobile-oriented development. New population growth and job opportunities are seen to locate in less dense urban suburbs, where accessibility and mobility are supported by new road infrastructure and intensive use of automobiles. For example, from 1950 to 1990, the U.S. population in the central cities remained while the suburban population almost doubled to a share of 65%. A greater difference is found in use of urban land area. Suburban land area takes up almost 80% of urban area in the year of 1990 (Nechyba & Walsh, 2004). With such low density and automobile-driven development, others call it urban sprawl, socio-economic and environmental problems came to our urban life: People have to travel longer both in time and distance; car ownership is increasing while the average vehicle occupancy is decreasing. Specifically, most cities are suffering from congestion in rush hours and the environment as a whole is changing dramatically (Dieleman & Wegener, 2004). In the long term, the emissions from the transport sector are increasing the global temperature and contributing to climate change. This offers planners a perspective to look further into urban transport and its climate impact.

1.1.3. Cycling—a sustainable mode and its success in Europe

Unlike motorized vehicles, cycling does not create noise and emissions and it consumes much less non-renewable resources and requires less space for use and parking (Buehler & Pucher, 2009). It is an environmentally friendly mode which should be promoted under any framework of sustainable transport. European cities have long been recognized for their ability to facilitate and encourage cycling much more than their North American counterparts. Successful examples are cities in The Netherlands, Denmark, and

Germany where cycling rates are the highest in the world (Pucher & Buehler, 2007). Cities such as Amsterdam, Groningen, and Münster, provide examples that even people are not economically deprived and can afford private cars, cycling is still appealing to them. Cycling not only creates environmental benefits for all as well as physical benefits for cyclists, but also helps to strengthen social inclusion and integrity since getting a bike is much cheaper in comparison to private cars (Pucher & Buehler, 2008).

1.2. Scientific justification

1.2.1. Emissions from transport sector

The transport sector is a significant contributor to greenhouse gases (GHG) emissions. According to Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (2011), 'the transport sector is responsible for about one quarter of global carbon dioxide emissions and emissions from this sector are growing more rapidly than any other.' For countries from the Organization of Economic Cooperation and Development (OECD) , as pointed out by the International Transport Forum, this figure goes up to 30% (OECD, 2010). Can the environment bear the increasing use of motorized vehicles? A concentration of CO2 in the atmosphere of 450 parts per million (ppm) is defined as sustainable, which means in the first half of this century a 42% reduction is required (Åkerman & Höjer, 2006). In 2009, there were 592 cars per 1,000 adult residents in The Netherlands; the total number of cars was estimated to be 7,584,112 (Ministry of Transport, 2010). This is almost a 10% increase compared to the number in 2004 (553 per 1000 adult residents, 6,901,993 in total) (Ministry of Transport, 2005). However, the actual amount of emissions is not only reflected by the number of cars but also by the use of cars, including frequency and distance. Many cities around the world are found to increase the total distance travelled by cars. Cameron, et.al (2004) portrayed the trends of VKT (vehicle kilometers of travel) for cities across the continents and found that all cities under their study have increased VKT from 1960 to 1990. The increase in VKT directly leads to increase in emissions. For example, Spain had 50% more emissions in 2005 compared to that in 1990, though only 15% increase was allowed (Bart, 2010). Particularly, the emissions from the transport sector were found to have doubled during the same time. Similar situations happened in other European countries such as Portugal, Greece, Italy, and Ireland. In conclusion, besides road safety, noise pollution, congestion caused by motorized vehicles, their GHG emissions, especially carbon dioxide, are long term concerns of sustainable development.

1.2.2. A zero-emission transport mode: cycling and its share in the Netherlands

Compared to the use of motorized vehicles, cycling is a zero-emission transport mode. Other advantages as summarized by Pucher and Buehler (2008) include its low cost, less space requirement, noise-free, etc. Despite the fact that the number of motorized vehicles has increased significantly, the Netherlands has been famous for its cyclist friendly urban design and policy and has a very large share of cycling trips. However, cycling in many industrialized countries is a marginal mode of transport, occasionally chosen by trip makers for recreational purposes but seldom used for utilitarian purposes (Pucher & Buehler, 2008). Unlike other metropolitan areas in the rest of the world, cycling in Dutch cities is not only for recreational use (less than 10%) (Ministry of Transport, 2010) but mostly a utilitarian travel mode. For cities in the developing countries cycling seems to be the major transport mode for the low income class, however, cycling in the Netherlands is less class-dependent and it embraces all walks of society. The bicycle ownership and share are among the highest in the world. According to the Physical Planning Department of Amsterdam (2006), cycling constitutes 37% share in urban transport and more than one third of her residents cycle to work. At the national level, the cycling share is reported to be 27% (2005) of trips for the Netherlands (Pucher & Buehler, 2008). Even the city with lowest cycling rate has a share of 15% (Fietsberaad, 2009a), which is more than most other European cities. Amsterdam—the cycling capital of Europe, is mostly flat and compactly covered by mixed use neighbourhoods. Together with its cycling friendly urban design, Amsterdam reaches the highest cycling share compared to any other capital cities

(Buehler & Pucher, 2009). Groningen is another successful case in creating a cycling environment for her citizens. With long established policy and planning support for cycling which ensures that most activities are within cycling distances, Groningen reaches a cycling share of 37%, almost the highest in the Netherlands (Fietsberaad, 2009a).

1.2.3. Climate Value of Cycling: Value what we have

However, unlike motorized vehicles whose negative impact on the environment in terms of emissions is self-evident, the positive effect of cycling is not easy to assess. Only by looking at the percentage of workers who cycle (Newman & Kenworthy, 1991) could not quantify the value of cycling since it lacks information of the distance travelled by cycling. Recently Massink et al., (2011) developed a modelling framework to calculate the most likely substitution mode for each bicycle trip and estimate the additional CO_2 emissions caused by the induced traffic if cycling would no longer be possible, which is called as the Climate Value of Cycling (CVoC) (Massink, et al., 2011). Assessing the CVoC for Dutch cities in terms of the contribution of cycling to the mitigation of GHG emissions is possible. This is particularly interesting since Dutch cities are known to have a good performance in cycling and so far there is no systematic assessment of cycling in terms of its climate value for the Netherlands. Assessing the CVoC could be operationalized by calculating how much emission a city saves through the use of bicycles (Massink, et al., 2011). This concept also incorporates social-economic characteristics of trips makers and trips characteristics through the way cycling trips are substituted by other modes using a behavioural model. Since the increasing population and urban development are pushing the growth of urban transport vice versa, a city with a large modal share of cycling can avoid carbon dioxide emissions significantly, which is one of the biggest challenges for sustainable transport. On the one hand, CVoC represents the avoided emission an urban system saves through its cyclists; on the other hand, it also represents the risk, or the undesirable emission which might be brought into our environment by substituted motorized vehicles if VKT for cycling decreases.

1.3. Problem statement

Though the cycling tradition in the Netherlands has long been established, a systematic assessment on cycling concerning its contribution to the environment from a climate change perspective is not yet done. Hence, quantifying the climate value of cycling for all Dutch cities and looking into their differences is needed. Since cycling as an individual mode is part of the transport system which is greatly influenced by land use, it is promising to incorporate urban form information to analyze if and how different dimensions of urban form (density, diversity, design) influence travel pattern, and further influence the climate value of cycling.

What is the CVoC for The Netherlands in general? How to understand different CVoC values for Dutch municipalities? Can some urban form indicators explain CVoC? How can interpretations of CVoC aid sustainable urban development and mitigation of GHG emissions? How does urban form affect CVoC to allow for urban transport and urban planning being effective? The questions above are important to understand the problem of the interactions of urban transport and land use and their impact on climate change. Answering these questions can help to understand CVoC and provide suggestions to planners and policy makers based on the level of CVoC of the municipality.

To answer these questions, it is important to recognize the interactions between transport, land use and climate change (section 1.3.1) and realize the importance of planning in reshaping urban transport (section 1.3.2 and 1.3.3). It is also necessary to discuss how urban form can influence travel pattern (section 1.3.4). Previous research studies which build link between urban form, transport and the environment focus mostly on energy consumption (Anderson et al., 1996; Mindali et al., 2004; Newman & Kenworthy, 1991).

It is then proposed to build a link between CVoC and urban form (section 1.3.5) with the concern that some urban forms are more sustainable—they have larger share in cycling and public transport and less use of private cars. This link connects the environment and our urban system (further presented in conceptual framework in Section 1.5).

1.3.1. Interactions between urban transport, land use, and climate change

The relation between urban land use, transport, and climate change has long been identified (Manheim, 1979), see Figure 1. Two factors are influencing the traffic flow—the transport system and the land use. The flow then will determine the GHG emissions which in the long term will lead to climate change. To understand their interactions, the feedback loops (Figure 1 the colour arrows) help us to take different spatial and temporal scales into account (Mehrotra et al., 2011). Their interactions call for sustainable urban transport and land use policies. However, the effects that land use and transportation cast on climate change need further exploration and this research will take one perspective to address this issue.

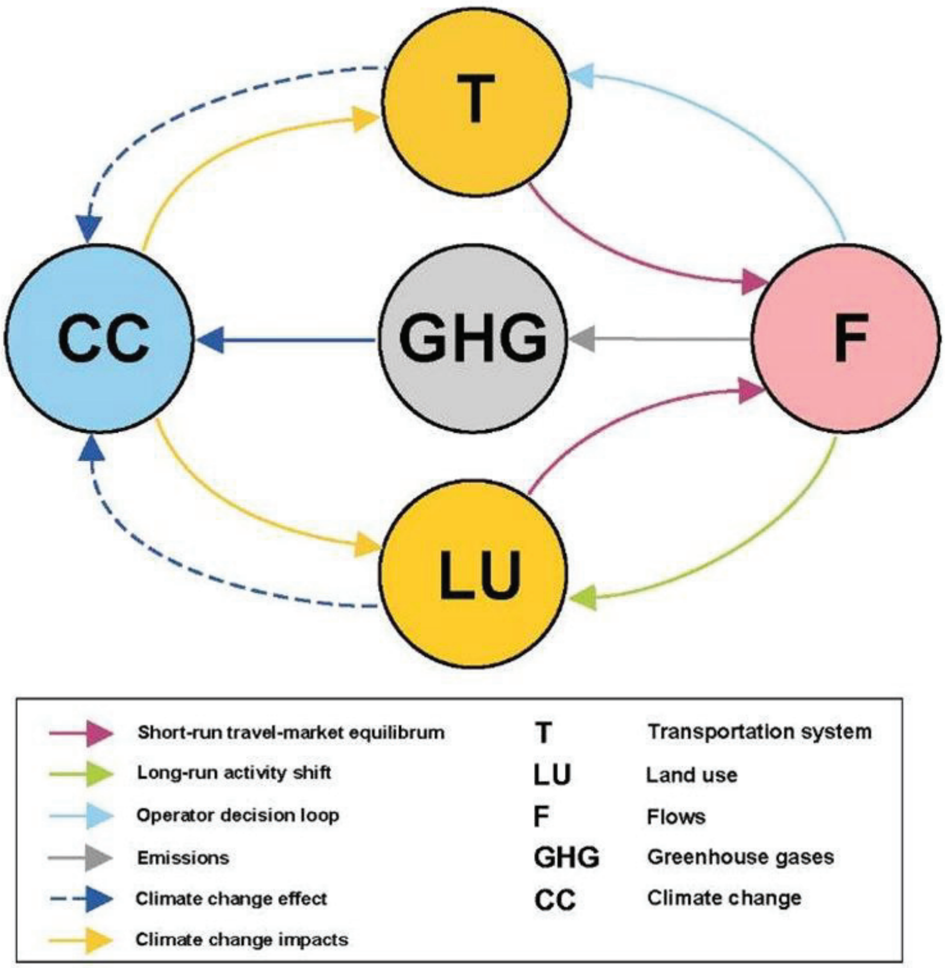


Figure 1 Urban transportation, land use, and climate change interactions
Source: H. Gercek (2011), adapted from Manheim (1979)

1.3.2. Reduction and avoidance of GHG emissions: Through technology or planning?

Technology alone to update vehicles and to produce clean fuel is never enough to reduce GHG emissions. Actually technology innovation still encourages the use of motorized vehicles by advertising that cars are less polluting and less energy consuming. However, the reason why worldwide responses to climate change mitigation had been focusing on technology is its acceptance from politicians (Frank et al., 2007). Planners on the other side, should and must participate in the endeavour to 'shrink the environmental footprint of the urban transportation sector' (Cervero & Murakami, 2010) through planning and design. To reorganize urban mobility is the best approach of climate mitigation in transport sector (Massink, et al., 2011). The sustainable strategies for urban transport and their impact on pollutant as well as GHG emissions are summarized by Dalkmann and Brannigan (2007). Despite the technology for clean cars and fuels which aims to improve its sustainability but still promotes the motorized transport, planners could think about how to reduce the travel demand of residents and how to shift them from motorized transport to non-motorized transport (NMT). To encourage and facilitate cycling is definitely one of the best ways for the second option. However, the use of bicycle differs greatly from one city to another. To cite Pucher and Buehler (2008), 'In the Netherlands, Germany and Denmark, cycling levels are more than ten times higher than in the UK and the USA.' This is reasonable as the level of cycling is dependent on many factors including the provision of infrastructure, related policy, urban form, etc.

1.3.3. Urban form and transport

The increasing recognition that modern cities are vulnerable to climate change requires our attention in addressing the interactions between transport and land use (Mehrotra, et al., 2011). To investigate how cities vary in modal split, the differences of the cities, especially the physical configurations, should first be identified. Land use is connected with transport through its distribution of different land use types (Wegener & Fürst, 1999). 'Increasing evidence suggest that the shape of a city and the land-use distribution determine the location of emission sources and the pattern of urban traffic …Land-use policy instruments in conjunction with other instruments at hand may be required to contain increasing emission from the transport sector' (Dulal et al., 2011). So, it is reasonable to assume that the physical form a city takes can greatly affect its transport system, physically and environmentally. One definition of urban form is 'the spatial configuration of fixed elements within a metropolitan region' (Anderson, et al., 1996). More specifically, it includes the spatial arrangement and density of land uses and the design of basic infrastructure such as roads. Usually, urban form reveals how different land uses are distributed and how people are moving through its transport system. There have been two conflicting urban forms: "urban sprawl" typically found in the North America and "compact city" of the European cities (Dieleman & Wegener, 2004; Frenkel & Ashkenazi, 2008). Under these two forms their transport patterns differ greatly: people in the U.S. drive 7000 kilometres more, and travel 1200 kilometres less by public transport than people in Europe each year (Newman & Kenworthy, 1991). A further step is to find what urban form factors are highly related to the use of motorized/non-motorized vehicles thus contributing to GHG emission. There are various research studies on this topic and many of them fall directly or indirectly within the discussion of density (Buchanan et al., 2006; Dulal, et al., 2011; Mindali, et al., 2004; Ryan & Throgmorton, 2003; Saunders et al., 2008; Scheiner, 2010; Sharpe, 1978).

1.3.4. What makes a difference: policy, physical structure, density, land use mix, urban design?

It is explained by Gordon and Richardson (1997) that the suburbanization in the U.S. and people's overwhelming choice of low-density settlements are due to the fact that more subsidies are given to auto travel than to public transit. The urbanization rate also plays an important role in determining urban transport. In a U.S. context, it is confirmed by Schwanen and Mokhtarian (2005) in four sequenced groups of urban consonant, urban dissonant, suburban dissonant and suburban consonant, that the probability of using private car increases while the probability of using public transit decreases. However, the physical neighbourhood structure, i.e. urban or suburban, has a greater influence on the commuter mode choice. It is concluded that though both neighbourhood physical structure and preference have impact on mode choice, the former is more powerful. Urban density has been studied for its impact on urban transport before and after the recommendation of returning to high residential densities and mixed land uses accepted by the Conference on Environment and Development held in Rio de Janeiro (1992). Newman and Kenworthy (1989) concluded a significant negative correlation of urban density and energy consumption in transport for 32 cities. This finding has been applied as recommendation for the development of "compact cities" in the European countries. Others have concluded on density for different scales. For example, it is proposed that the largest reduction of VKT would come from compact communities where the roadway provision is below average (Cervero & Murakami, 2010). This brings the dimension of density down to a localized level. Besides density, mixed land use and urban design are also hypothesized as explanations for urban transport. Mixed land use shortens the distance between residential place, work place, and shopping places so it plays an important role in reducing the demand of transport (Grazi & van den Bergh, 2008). Urban design also influences people's decision of mode choice. People prefer to cycle in a safe and pleasant environment in which they find separate cycling path, street trees, lights and etc. Proper urban design can make destinations more accessible and make trips makers more comfortable with the provision of facilities, infrastructure, and proximity to them (Cervero & Kockelman, 1997). Badland and Schofield (2005) argued that the low cycling rate in non-European cities is due to the lack of cycling infrastructure and the proximity to the infrastructure. This is supported by a study in Australia showing that residents within 1.5 km of cycling trail use the infrastructure one more hour per capita per week than those who reside more than 1.5 km to the cycling trail (Merom et al., 2003). Other urban design issues such as to increase the connectivity of infrastructure receives little attention in literature. Cervero and Kockelman (1997), who argued that 'density issues have long been acknowledged while diversity and design have long been ignored', were among the first to combine three dimensions of urban form, i.e. density, diversity and design to study the travel demand and according to them the influence of each dimension varied from modest to moderate in a U.S. context.

1.3.5. Building a link between CVoC and urban form in the Netherlands

The concept of CVoC provides us with a new perspective to look into the urban transport system and how cycling plays an important role in reducing and avoiding GHG emissions and achieving sustainability. It not only represents the human efforts of protecting the environment through their daily travel using bicycle but also reveals the structure of competing modes. There are two directions of looking at CVoC—modal split and urban form, which are interrelated. Modal split directly explains CVoC while urban form is reported to influence modal split since different urban forms create different travel patterns. Previous studies might have started from various perspectives ranging from socio-demographic characteristics to physical structure of urban areas. For planners, as it is hardly possible to change the demographic structure of the society (income groups, social status, car ownership, family structure, etc.), a more promising and effective way is to study how urban form functions in explaining the CVoC. The travel behaviour in Dutch monocentric and polycentric urban systems are studied and the results on the urban form in respect to modal choice and distance travelled are mixed (Schwanen et al., 2001). However, one of their conclusions that decentralization to less dense urban area results in decrease of cycling and increase of car use do lend credibility for further studies with deeper insights on urban forms. Experiences could be learned from the study by Cervero and Kockelman (1997) in which three dimensions of urban form, i.e. density, diversity and design are included in respect to travel behaviour.

1.3.6. Understanding the problem—what does CVoC tell?

The value of CVoC represents how much emission an urban system saves through cycling. These emissions will possibly be emitted if cycling is no longer a mode choice for these trip makers. In this case CVoC is symbolizing a risk of possible emissions from the urban transport system. It not only values what cyclists are saving but also quantifies the risk of sustainability of an urban system. Two cities which have the same PKT for cycling might have a different CVoC. Because these distances travelled by cycling might be substituted by modes (private cars, public transport, walking, etc.) with different compositions which make their CVoC different. So a city has a higher risk if its cycling trips are substituted more by private cars than by other modes. Since each urban form dimension alone cannot explain the pattern of urban transport and its climate impact (in this research, CVoC in particular) perfectly, it is promising to incorporate them into a set of variables and investigate their relation with the climate value of cycling. In short, this research will answer the following questions. How is urban form associated with its transport sector through the Climate Value of Cycling? What is the risk of additional emissions for an urban system? How is the risk related with urban form? Which municipalities may have higher risk, and which may have lower risk, and what are planning and policy suggestions to them, respectively? How does population density, activity density, level of urbanization, land use mix, urban design influence the level of risk?

1.4. Research objectives, questions and hypotheses

The aim of this research is to assess the Climate Value of Cycling for Dutch cities under different urban forms. This could answer the question "what urban form makes a city more sustainable from the perspective of its climate value of cycling".

1.4.1. Objectives

Objectives of this research are to (1) operationalize the assessment of CVoC ;(2) quantify urban forms of Dutch cities from different dimensions; (3) determine the relation between urban form and CVoC; and (4) provide planning and policy suggestions for sustainable urban development.

1.4.2. Research questions

1.1 What is the modal split of cycling for each municipality?
1.2 What is the total distance travelled using cycling?
1.3 How to classify all the trips?
1.4 How to substitute the cycling trips by other modes?
1.5 What are the emission factors for each mode?
1.6 What is the Climate Value of Cycling for each Dutch city?
2.1 What urban form dimensions and their indicators are possibly related to modal split?
2.2 How to quantify each urban form indicator?
3.1 What is the relation between CVoC and urban form?
3.2 Whether thresholds exist and if so what are the thresholds for each indicator?
4.1 What suggestions can be made to encourage sustainable urban transport?
4.2 What are the policy/planning implications of the result?

1.4.3. Hypotheses

This research will test the associative relation between the physical form cities take and their Climate Value of Cycling in The Netherlands. Several urban form indicators will be included. They are classified into three categories, namely Density, Diversity, and Design (3D). Since the CVoC is determined by both the total cycling distance and the emissions from the most likely mode to substitute, based on the previous arguments and the literature review, the hypotheses would be:

Table 1 Research hypotheses

Dimension	Hypothesis
Density	The higher the density, the lower the unit CVoC.
Diversity	The more diverse and mixed land uses, the lower the unit CVoC.
Design	The more pedestrian and cyclist friendly urban design, the lower the unit CVoC.

Unit CVoC is the climate value of cycling per kilometre. A higher Unit CVoC suggests that when cycling is no longer a mode choice, the rest of the transport system would be less sustainable; a lower Unit CVoC suggests that when cycling is not possible, the cycling trips will be substituted by modes with fewer emissions, indicating a more sustainable transport system.

1.5. Conceptual framework

Five main concepts are included in this framework after the literature review. The red line represents the relation this research will address: the association between urban form and CVoC. Other concepts are directly or indirectly mentioned and connected to this research in different stages. To assess the climate value, modal split information is needed. The behavioural model to substitute cycling trips will estimate the most likely alternative based on the overall travel behaviour in a trip bin. Meanwhile, the effects that urban forms have on travel pattern and modal split have been discussed in details in the previous sections. These five elements are organized in three layers: "Environment", "Urban System", and "Socio-economic" respectively and these three layers together are components of the urban dynamics—"interactions between people, urban form and transport produces commuter patterns with social, economic and environmental outcomes"(Mehrotra, et al., 2011).

Table 2 Elements in conceptual framework

Urban Form	Travel Pattern	Modal Split	Socio-economic	CVoC
Density	Trip length	Motorized vehicles (private cars and public transport)	Car ownership	Cycling distance and its climate value
Diversity	Trip purpose	Cycling	Travel behaviour	Avoided emissions and risk
Design	Mode choice	Walking	Other	Policy implications

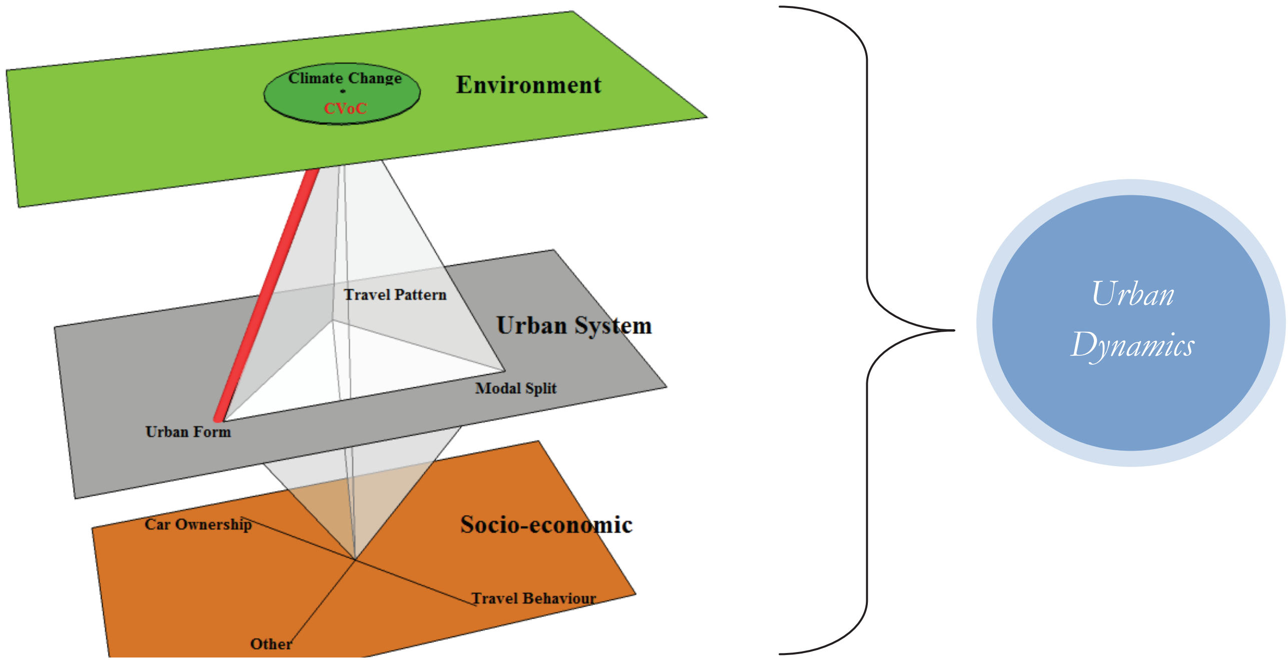


Figure 2 Conceptual framework

2. LITERATURE REVIEW

2.1. Cycling tradition in the Netherlands

If Europe is the continent suitable for cycling, then The Netherlands is the paradise for cyclists. With 26 % (2006) of all trips occurring by bicycle, The Netherlands towers above the rest of Europe. There are some statistics that 36% of short trips (less than 5 km) by the Dutch are made by bicycle, and 18% of the Dutch travel time is spent on the bicycle. Though often associated with recreation, cycling in The Netherlands covers a large variety of purposes. Top cycling trips are made for the purposes of shopping (22%), education (18%), and commuting (17%). Since cyclists have to generate their own energy to ride a bicycle, cycling trips are sensitive to trip distances. Bicycle use occurs more in short distance trips than in long distance ones. For certain age groups, cycling is the dominant transport mode, for example teenagers. From the age of 18 (possessing a driver's license and student public transport pass), though more alternatives are available, the cycling share remains high till late in life (over 75) when the physical conditions cannot meet the requirements of cycling (Loon & Broer, 2006).

However, cycling shares in The Netherlands fell dramatically in the nineteen sixties and seventies due to the increasing car ownership and use, suburbanization and car-oriented transport policies. Luckily the image of cycling gradually increased since the end of the seventies, by when the first bicycle policy plans were written. Cycling started to recover in the eighties (Fietsberaad, 2009b).

Overall speaking, cycling is highly interwoven with Dutch culture. The word "culture" as it is used here is not the culture you find in museums but the daily behaviour, the norms and values that regulate the Dutch society. Cyclists have neither high nor low status since cycling in the Netherlands is a class-free transportation means and is not linked with social status and identity (Pettinga, 2005). There are many factors influencing the decision of the trip maker whether to choose the bicycle, including distance, purpose, weather condition, safety, parking, how much luggage, etc. In a Dutch report on short distance trips, Jansen et al.(2006) recorded the arguments of car owners in favour of the bicycle for a short errand. 70% of them find cycling good for their health and also good for the environment, which suggests that the public awareness of cycling, especially for the environment is quite strong. Top reasons of using a car are: large amounts of luggage to carry (90%) and bad weather (79%).

2.2. Benefits of cycling

Introduced in the first chapter, a wide range of the benefits of cycling is covered by literature. From the perspective of health in a Dutch context, it is concluded that though individuals who shift themselves from car drivers to cyclists will expose themselves to air pollution and bear the risk of accident, the beneficial effects of cycling will bring them 9 times more life-years than they will lose, based on the estimation that the life expectancy will be increased by 3 to 14 months with regular cycling while the lifetime lost because of air pollution and accident will be 0.8 to 40 days and 5 to 9 days respectively. The benefits of health are higher when the society as a whole is included because the pollutant air emissions are reduced (de Hartog et al., 2010). A more recent study carried out similar health impact assessment based on the results of a comprehensive European Commission research on "External Costs of Energy", which allowed them to assess for each individual driver who switches to active transport (cycling and walking), the health benefit of physical activity, the health benefit for the general population due to reduced pollution, the change in air pollution impacts for the individuals who make the change, and changes in accidents (Rabel & Nazelle, 2012).

Cycling is environmentally sustainable because it requires much fewer raw materials for manufacturing and has no energy consumption and no emission. It does not create noise on the road; Cycling is economically sustainable because getting a bicycle is inexpensive compared with getting a private car. Neither does it require much maintenance. More importantly, providing cycling infrastructure requires much less space than infrastructure for private cars and public transport that require a large amount of monetary support from the government; Cycling is also socially sustainable because everyone can get a bicycle due to its low price, which makes cycling the most equitable transport mode among others (Pucher & Buehler, 2008).

2.3. Concept of Climate Value of Cycling

The climate impact of transport systems is usually evaluated through pollutant emissions and GHG emissions from motorized vehicles. The combustion of large amounts of fossil fuels leads to significant emissions which accelerate the environmental pollution and climate change in the long term. However, the value of non-motorized vehicles (NMT), mainly the use of bicycles, has long been ignored for its contribution to climate mitigation. From the point of view that each bicycle trip might be substituted by other motorized modes thus inducing emissions, Massink, et al., (2011) recently came up with this climate value concept for cycling. Its counterpart in the field of economics is usually termed "opportunity cost" while in transport economy another term "avoidance costs"(Bickel & Friedrich, 2001) is used referring to the external effect of CO_2 emissions, for which motorized modes have a positive value. Based on these concepts, they concluded that bicycles trips have negative environmental cost, i.e. a positive contribution because the avoidance costs for bicycle trips are zero while costs for their alternatives are non-negative (zero for walking, positive for other motorized modes). Based on a prediction of the most likely substitution mode for each bicycle trip and the emissions generated by that mode, it is possible to calculate the total avoided CO_2 emissions which then represent the Climate Value of Cycling for the area being studied.

2.4. Climate mitigation in transport sector

It is summarized by Cervero and Kockelman (1997) that some urban design philosophies such as new urbanism and transit-oriented development helped to reconstruct the urban transport system and to reshape travel demand. According to the authors, they share common transport objectives:

> "(1) reduce the number of motorized trips, what has been called trip degeneration; (2) of trips that are produced, increase the share that are non-motorized (i.e. by foot or bicycle); and (3) of the motorized trips that are produced, reduce travel distances and increase vehicle occupancy levels (i.e. encourage shorter trips and more travel by transit, paratransit, and ride-sharing)." –(Cervero & Kockelman, 1997)

Similarly, Dalkmann and Brannigan (2007) summarized three primary ways to reduce GHG emissions from the transport sector, namely (1) to avoid travel demand, (2) to shift to more sustainable modes, and (3) to improve the sustainability of modes. There are some transport policy instruments under the framework of the three strategies, namely planning, regulatory, economic, information and technological. From the planning perspective which addresses "Avoid" and "Shift", urban activities and residents could be rearranged much closer so that there is more inclination to NMT (walking and cycling) when distances are shortened and travel demand is reduced. Moreover, by providing public transport facilities and pedestrian and cycling infrastructure, people might be more willing to shift to public transport and NMT.

2.5. Urban form dimensions in respect to travel pattern

There have been many studies which addressed the relation between the dimension of density and travel demand (Buchanan, et al., 2006; Dulal, et al., 2011; Mindali, et al., 2004; Newman & Kenworthy, 1989; Ryan & Throgmorton, 2003; Saunders, et al., 2008; Scheiner, 2010; Schwanen & Mokhtarian, 2005; Sharpe, 1978). Most of their findings agree on the notion that high urban density, or more compact urban form has a significant negative correlation with travel demand and CO_2 emissions. Evidence from mixed land use is much fewer. However, it is found that the change in mixed land use from very low to very high leads to a 2 kg CO_2 emission reduction per capita per day from vehicle travel (Frank, et al., 2007). Mixed land-use has the ability to reduce motorized travel, redistribute the travel volume throughout the day, increase vehicle occupancy and public transport, and increase the efficiency of parking (Cervero, 1988). The effect of mixed land use on reducing travel demand is explained by Cervero and Kockelman (1997). By putting convenience stores within neighbourhoods and retail stores, restaurants, and service outlets within working places it is possible to reduce travel demand. In a mixed land-use area, many trips are internalized in the immediate environment and to a large extent such internalized trips are made by walking and cycling. For the dimension of design, Badland and Schofield (2005) argued that higher street connectivity and pedestrian and cycling friendly urban design can greatly encourage bicycle use without which many cities are found to have a very low cycling rate.

2.6. How to quantify each dimension of urban form

2.6.1. Density

The density of the built environment is often defined by population density (population per developed acre) or employment density (employment per developed acre). Besides, accessibility to jobs is regarded as a proximity to the compactness of land use and an indicator of commercial intensity (Cervero & Kockelman, 1997). An international review (Stead & Marshall, 2001) covering studies between 1980 to 2000 suggests that measurement of density is mostly about population density while few literature includes employment density. However, employment density is reported to be capable of explaining variation in three mode choices for work trips and shopping trips (Frank & Pivo, 1994). Spatial scale of density is discussed by others with the concern that different parts of the city (CBD, inner city, outer city) have different influence on travel pattern (Mindali, et al., 2004).

2.6.2. Diversity

As an aggregated measure of the mixed land-use (Cervero & Kockelman, 1997), land use diversity is commonly represented by the ratio of jobs to workers resident in the area (job ratio)(Stead & Marshall, 2001). Other quantifications of land-use mix are the entropy value (a function of family types, retail and services, office, entertainment, institution, and industrial area) (Frank & Pivo, 1994) and Land-use mix diversity (a function of residential, commercial, and office/other area)(Bhat & Guo, 2007). See below:

Level of land use mix (entropy value) =
- [single family • log10 (single family)]
+ [multifamily • log10 (multifamily)]
+ [retail and services • log10 (retail and services)]
+ [office • log10 (office)]
+ [entertainment • log10 (entertainment)]
+ [institutional • log10 (institutional)]
+ [industrial/manufacturing • log10 (industrial/manufacturing)]

Figure 3 Formula of land use mix #1

Source: (Frank & Pivo, 1994)

$$\text{Land-use mix diversity} = 1 - \left\{ \frac{\left|\frac{r}{L} - \frac{1}{3}\right| + \left|\frac{c}{L} - \frac{1}{3}\right| + \left|\frac{o}{L} - \frac{1}{3}\right|}{4/3} \right\},$$

Where $L = r + c + o$, and r is the zonal acreage in residence use, c is the acreage in commercial/industrial use, and o is the acreage in other uses.

Figure 4 Formula of land use mix #2

Source: (Bhat & Guo, 2007)

2.6.3. Design

Design relates to the way how different parts of the built environment are connected. It is about the characteristics of the streets pattern (proportion of intersections, freeway miles, number of blocks and dead ends, etc), the provision and distribution of pedestrian and cycling infrastructure, and site design (Cervero & Kockelman, 1997). Studies vary in the description and quantification of the dimension of design. Streets, pedestrian and cycling provisions, and site design are included by Cervero and Kockelman (1997) using a random sample of 20 blocks by taking their average. Bhat and Guo (2007) use local transportation measures including the cycling path density (miles of bikeway facility per square mile). Proximity to transport network and availability of residential parking and provision of local facilities are reviewed by Stead and Marshall (2001).

3. RESEARCH DESIGN AND METHODOLOGY

3.1. Research design

A quantitative analysis will be carried out in this study to build the link between Climate Value of Cycling and urban form for Dutch cities. The quantification of CVoC would follow the approach of Massink, et al (2011) in which a behavioural model of mode choice will be used to estimate the most likely modes to substitute cycling trips assuming cycling is no longer an alternative. Relevant programming is needed in case of data complexity and large data size. A selection of urban form indicators in respect to its three dimensions will be based on literature review, as well as data availability. Statistical analysis will be used to test the associative relation between the two concepts. A complete research design and operational plan is outlined in Figure 3 in which five phases are included.

This research is highly dependent on data availability. Without a large dataset containing travel diaries as well as other information, it is impossible to quantify CVoC. The national mobility survey—MON (Mobiliteitsonderzoek Nederland) from 2004 to 2009 is available in this research. Further data requirements are met with data sources, such as CBS (Statistics Netherlands) and some geographical information providers by whom relevant GIS layers are made available. The data processing phases conducted using Matlab scripts adapted from Massink, et al (2011), which allows to handle the large volume of data in MON.

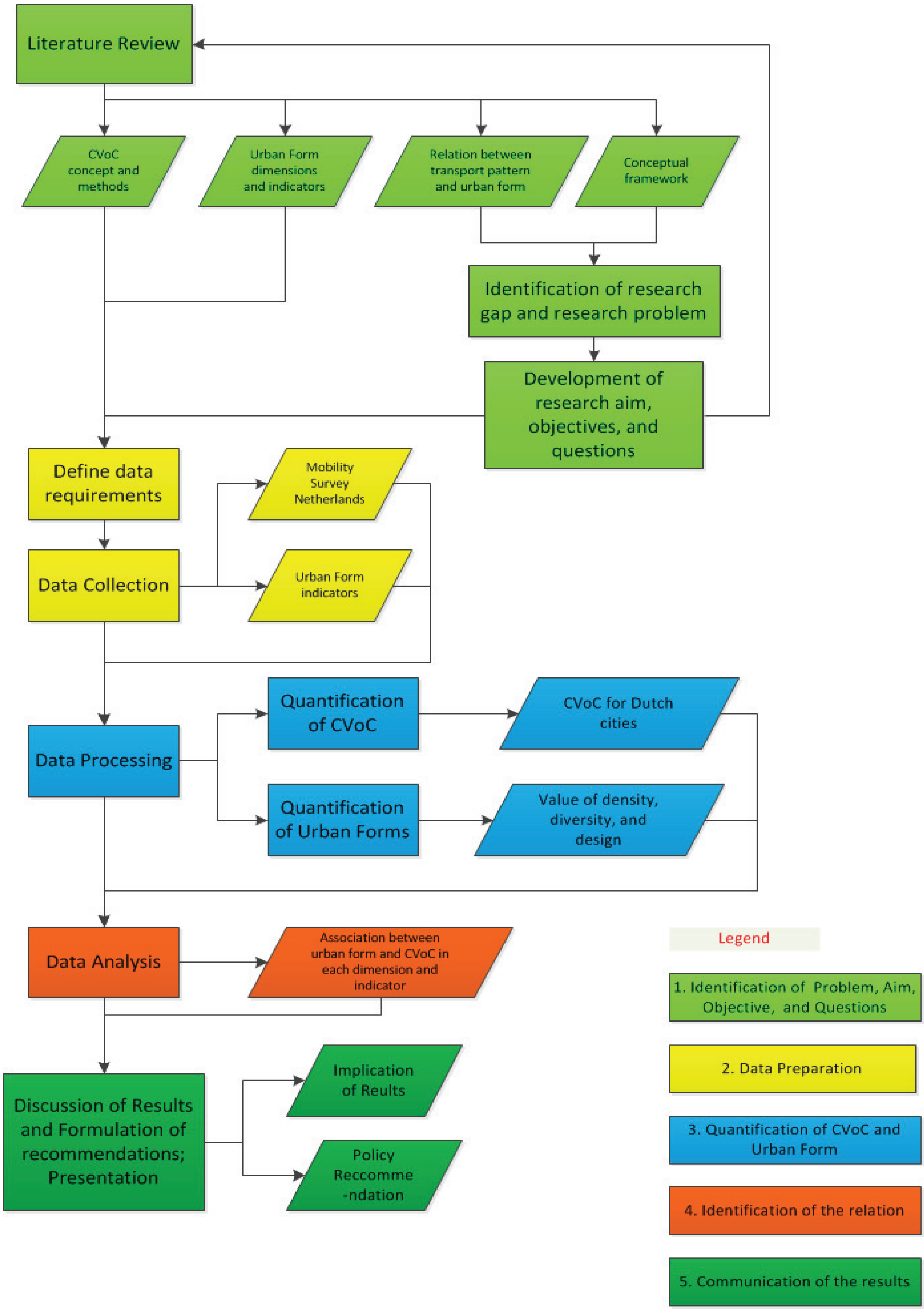


Figure 5 Research design and operational plan

Table 3 Research questions and methods

Research Question	**Method**	**Data Requirement**	**Source**	**Stage in operational plan**
1.1 What is the modal split of cycling for each municipality?	Quantitative operation on travel data	Travel diary for each city	Mobiliteitsonderzoek Nederland: Mobility Survey Netherlands	3
1.2 What is the total distance travelled by cycling?	Quantitative operation on travel data	Travel diary for each city	Mobiliteitsonderzoek Nederland: Mobility Survey Netherlands	3
1.3 How to classify all the trips?	Literature review and statistical analysis	Travel diary for each city, with information on trip characteristics	Mobiliteitsonderzoek Nederland: Mobility Survey Netherlands	1,3
1.4 How to substitute the cycling trips by other modes?	Literature review and modelling the behaviour of mode choice	Modal share in each cluster	Mobiliteitsonderzoek Nederland: Mobility Survey Netherlands	1,3
1.5 What are the emission factors for each mode?	Literature Review	Literature	Literature	1
1.6 What is the Climate Value of Cycling for each Dutch city?	Quantitative operation based on substituted cycling trips	Total cycling distance, percentage of each mode to substitute, emission factors	Mobiliteitsonderzoek Nederland: Mobility Survey Netherlands	3
2.1 What urban form dimensions and their indicators are possibly related to modal split?	Literature review	Literature	Literature	1
2.2 How to quantify each urban form indicator?	Literature review	Literature	Urban form data (to be decided), Literature	1,2
3.1 What is the relation between the climate value of cycling and urban form?	Regression & correlation analysis, or other statistical methods	CVoC and quantified urban form indicator for each city	Data processing based on acquired data in stage 2	3,4
3.2 Whether thresholds exist and if so what are the thresholds for each	Plotting; Statistical method	CVoC and quantified urban form indicator for each city	Data processing based on acquired data in stage 2	4

indicator?				
4.1 What suggestions can be made to encourage sustainable urban transport?	Literature review, discussion of results in this research	CVoC and Urban form relation results	Data analysis based on stage 3	5
4.2 What are the policy/planning implications of the result?	Literature review, discussion of results in this research	CVoC and Urban form relation results	Data analysis based on stage 4	5

3.2. Research methodology

3.2.1. Data preparation

This research mainly requires data from the transport sector and the land use sector for the Netherlands. Data from the transport sector include the Dutch Mobility Survey--MON (in Dutch: Mobiliteitsonderzoek Nederland) and the ArcGIS shapefile of roads. Data from the land use sector requires the ArcGIS shapefile of Dutch municipalities.

The Dutch Mobility Survey collects annual information regarding the mobility of the Dutch population. Travel data are collected on the transport movement of individuals, such as the purpose of the movement, the place of departure and destination, the transport mode, the travel time and distance. Social and economic information on individuals and households are also collected. Started in 2004, each year some 50,000 individuals are surveyed across the country with a total amount of sample trips of around 130,000. Weighting and scaling up through expansion factors renders the numbers representative for the entire Dutch population (DANS, 2009; Ministry of Transport, 2010).

The ArcGIS shapefile of Dutch municipalities with demographic and social as well as economic information is derived from the Dutch Neighbourhood Map 2008, 2009 (in Dutch: Buurtkaart met cijfers 2008, 2009), which are available at CBS (in Dutch: Centraal Bureau voor de Statistiek) (CBS, 2009b, 2010). Finally, the ArcGIS shapefile of Dutch roads is extracted from CloudMade data (http://cloudmade.com) derived from OpenStreetMap (http://www.openstreetmap.org) and are licensed under the terms of the Creative Commons Attribution Share-Alike 2.0 license. They are made available by MapCruzin (http://www.mapcruzin.com).

3.2.2. Data processing

3.2.2.1. Model description

The modelling methodology in this research follows the framework described by Massink, et al., (2011). The purpose of modelling is to estimate the most likely substitution mode for each bicycle trip and to quantify the induced CO_2 emissions of the substitution mode. Massink, et al., (2011) designed the model based on existing theories of the multinomial logit behavioural model, which defines mode choice situations based on the length and purpose of a trip and the socio-economic background of the trip maker. Thus the data input includes the present traffic characteristics at trip level with information on trip length, socio-economic background of trip maker and trip purpose. In the model trips which share the similar values of the above mentioned characteristics are grouped into one class—a 'trip bin'. In the same trip bin, all trip makers share the same background information, so these bins are defined as mode choice situations(Massink, et al., 2011). All trips sharing the same mode choice situations are clustered into the same trip bin regardless of their transport modes. Then bicycle trips in each bin are substituted by the most likely alternative modes according to the modal split of the rest modes in the bin.

The underlying assumption is that the probability ratios of choosing one mode over the other remain unchanged when the bicycle mode is excluded from the choice set (Massink, et al., 2011), which is a major property of the multinomial logit model, described by Luce and Suppes (1965) as the Independence of Irrelevant Alternatives (IIA) axiom, i.e. as cited by Massink, et al., (2011), "Where any two alternatives have a non-zero probability of being chosen, the ratio of one probability over the other is unaffected by the presence or absence of any additional alternative in the choice set". The interpretation of the IIA in this research would be that when cycling is taken out of the choice set, the ratios of probabilities between the other modes remain the same—the utility values of other modes are not affected by the presence or absence of cycling. Justified by Massink, et al., (2011) that in their research their trip classes are so small that each trip bin could capture the preference of individuals related to socio-economic stratum and purpose of trip. However, statistically IIA should be tested using the Hausman and the Small-Hsiao test (Hausman, 1978; Small & Hsiao, 1985).

Similar modelling steps (Massink, et al., 2011) are taken to quantify CVoC: (1) putting all trips with similar choice situation in the same trip bin; (2) calculating induced traffic (in this research discouraged traffic is not considered, further explained in Section 3.2.2.3); and (3) calculating opportunity costs. Here the original equations are presented as following:

Equation (1) is derived to estimate the alternative modes; Equation (2) shows the probability that mode *m* is the alternative mode for a bicycle trip in subclass *b*, *s*, *p*. Equation (3) calculates the induced traffic effect for mode *m* in each subclass: trip length bin *b*, socio-economic stratum *s* and trip purpose *p*. Finally equation (4) calculates the climate value of cycling by multiplying the induced traffic per mode with a modal emission factor (See Figure 6).

In this research, since more than 400 Dutch municipalities would be modelled for their CVoC, the choice sitation each trip bin represents only considers the length of the trip. Socio-economic backgrounds and the purpose of trip is not considered for the behavioural model. So *s* and *p* in the following equations are not included in this research. It is definitely a limitation but considering the large volume of data and number of municipalities to model, these two factors are excluded. The IIA violation in this research is not tested, which is another limitation.

$$f_{x_{b,s,p}}(x_{b,s,p}) = \Pr(X_{b,s,p} = x_{b,s,p}) = \Pr(\{m_{b,s,p} \in M_{b,s,p} : X_{b,m,p}(m) = x_{b,s,p}\}) \qquad \forall b, s, p \qquad (1a)$$

$$= \Pr(\{m_{b,s,p} \in M_{b,s,p} : X_{b,m,p}(m) = x_{b,s,p}\}) \qquad \forall b, s, p \qquad (1b)$$

$$= \Pr\left(\left\{m_{b,s,p} \in M_{b,s,p} : X_{b,m,p}(m) = \frac{N^m_{b,s,p}}{\sum_{m=1}^{m} N^m_{b,s,p}}\right\}\right) \qquad \forall b, s, p \qquad (1c)$$

$$P(X_{b,s,p}(m) = x_{b,s,p}) = \left[\frac{N^m_{b,s,p}}{\sum_{m=1}^{m} N^m_{b,s,p}}\right] \qquad \forall m, b, s, p \qquad (2)$$

where:

- b trip length bin b;
- s socio-economic strata;
- p trip purpose p;
- $m_{b,s,p}$ mode m in subclass: trip length bin b, socio-economic strata and trip purpose p;
- $M_{b,s,p}$ sample space M for subclass: trip length bin b, socio-economic strata and trip purpose p;
- $N^m_{b,s,p}$ number of trips of mode m in subclass: trip length bin b, socio-economic strata and trip purpose p.

$$\Delta PKT_m = \sum_{p=1}^{p}\left[\sum_{s=1}^{s}\left[\sum_{b=1}^{b}\left(F^s_{DT} * N^{bicycle}_{b,s,p} * (P(X_{b,s,p}(m) = x_{b,s,p}) * (\mu^m_{b,s,p})\right)\right]\right] \qquad \forall m \qquad (3a)$$

$$= \sum_{p=1}^{p}\left[\sum_{s=1}^{s}\left[\sum_{b=1}^{b}\left(F^s_{DT} * N^{bicycle}_{b,s,p} * \left[\frac{N^m_{b,s,p}}{\sum_{m=1}^{m} N^m_{b,s,p}}\right] * \mu^m_{b,s,p}\right)\right]\right] \qquad \forall m \qquad (3b)$$

Where:

- ΔPKT_m induced traffic of mode m in subclass: trip length bin b, socio-economic strata and trip purpose p;
- F^s_{DT} discouraged traffic factor specified per socio-economic strata;
- $N^{bicycle}_{b,s,p}$ number of bicycle trips in subclass: trip length bin b, socio-economic strata and trip purpose p;
- $\mu^m_{b,s,p}$ average trip length in subclass: trip length bin b, socio-economic strata and trip purpose p.

or climate value of cycling is calculated by multiplying the induced traffic per mode with a modal emission factor. The climate value of cycling is finally calculated by:

$$CV_{cycling} = \sum_{m=1}^{m} \Delta PKT_m * EF_m \qquad (4)$$

where:

- $CV_{cycling}$ climate value of cycling (kg CO_2);
- EF_m emission factor for mode m in kg CO_2 / km.

Figure 6 Original equations in the study of Massink, et al., (2011)

3.2.2.2. Modelling CVoC of Dutch Cities

For the Climate Value of Cycling part, according to the methodology introduced by Massink, et al., (2011), a series of Matlab programming scripts are used to estimate for each municipality how much carbon dioxide emission was saved in the year of 2008 through cycling. The CVoC is estimated based on the cycling trips with the same departure municipality, which means both inter-city trips and intra-city trips are included and the final CVoC is assigned to the municipality in which the trip starts. In principal, the CVoC for inter-city trips should be divided and assigned to the departure municipality and their destination municipality based on the distance travelled in each. However, separate distances in each municipality for inter-city trips are not available. Considering climate value as a macro level concept and the departure location can mostly influence the mode choice of the trip maker, in this research CVoC is attributed to its departure municipality for inter-city trips.

After the database is prepared for each municipality, a series of trip bins are constructed. In the Bogotá case study (Massink, et al., 2011), an interval of 5 km is used up to 30 km (30km and above are all in one trip bin). In this research, an interval of 5 km would make the first trip (0-5 km) bin very crowded, with 62% of all trips and 82% of cycling trips (see table 4 and 5 below). So an interval of 2 km is chosen, and trips with distance longer than 20 km are all grouped in the last trip bin. This is because cycling trips in Bogotá are comparatively longer than cycling trips in The Netherlands.

Table 4 Frequency table of trip distances (trips with all modes) in 2008

Trip distance (km)		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Trip abroad	9	.0	.0	.0
	0,1 - 0,5	12790	9.2	9.7	9.7
	0,5 - 1,0	14971	10.8	11.4	21.1
	1,0 - 2,5	33764	24.4	25.6	46.7
	2,5 - 3,7	13673	9.9	10.4	57.1
	3,7 - 5,0	6379	4.6	4.8	61.9
	5,0 - 7,5	13902	10.1	10.6	72.5
	7,5 - 10	5567	4.0	4.2	76.7
	10 - 15	8366	6.0	6.4	83.1
	15 - 20	5032	3.6	3.8	86.9
	20 - 30	6071	4.4	4.6	91.5
	30 - 40	3408	2.5	2.6	94.1
	40 - 50	2001	1.4	1.5	95.6
	>= 50	5812	4.2	4.4	100.0
	Total	131745	95.3	100.0	
Missing	System	6551	4.7		
Total		138296	100.0		

Table 5 Frequency table of trip distances (cycling trips only) in 2008

Trip distance (km)	Frequency	Percent	Valid Percent	Cumulative Percent
Valid 0,1 - 0,5	1441	4.4	4.4	4.4
0,5 - 1,0	4326	13.2	13.2	17.6
1,0 - 2,5	14110	43.1	43.1	60.7
2,5 - 3,7	5141	15.7	15.7	76.4
3,7 - 5,0	1875	5.7	5.7	82.2
5,0 - 7,5	3235	9.9	9.9	92.0
7,5 - 10	971	3.0	3.0	95.0
10 - 15	1055	3.2	3.2	98.2
15 - 20	302	.9	.9	99.2
20 - 30	206	.6	.6	99.8
30 - 40	48	.1	.1	99.9
40 - 50	12	.0	.0	100.0
>= 50	11	.0	.0	100.0
Total	32733	100.0	100.0	

Originally, there are more than 20 transport modes in the MON data. However, this does not mean they are all necessary to be considered and used to substitute cycling trips. Some of them are long distance travel, for example airplane; some of them are movements of personal recreation such as skating; some of them are movements of professions, such as tractor.

It is possible to convert those modes to the modes set which is composed of walking, cycling, driving, taxi, 2W/3W, bus, BRT, MRT, LRT, and other, since the Asian Development Bank (ADB) has quantified the emission factors for them, which are also used in the Bogotá case. However, since the emission factors for transport modes are regionally bound and only fit the situation of Asian countries where the public transport has very high ridership making the average emission factors for bus, train, tram, and metro very low, using such emission factors would certainly lead to distortion and bias in terms of the total CVoC.

Despite the major transport modes, many of them account for less than 0.5% (some even less than 0.1%) in the modal split. So it is necessary to make a simplified set of transport modes. In this research, the criterion is to keep all modes with modal share larger than 0.5% both in terms of trips and passenger kilometre travel (PKT) (see table 9 and 10) and convert the rest of them as a group "others". With support from a Dutch report (den Boer et al., 2008), the emission factors for them are also available (see table 8).

The emission factors for the Dutch transport system are derived from the report of CE-DELFT (den Boer, et al., 2008). Most public transport modes in The Netherlands have higher emission per kilometre because the ridership is much lower than that in the Asian developing countries. As compared in table 7 and 8 below, their differences are quite big (250% to 500%).

Table 6 Original modes and conversion

Code 0	Modes in MON	Transformed Code 1 (see table 8)
1	Te voet (walking)	1
2	Fiets (cycling)	2
3	Bestuurder auto (car driver)	4
4	Passagier auto (car passenger)	5
5	Bus	6
6	Tram/Metro	7
7	Trein (train)	8
8	Taxi	4
9	Fiets als passagier (bicycle passenger)	2
10	Snorfiets (motorcycle)	3
11	Bromfiets (motorcycle)	3
12	Motor/Scooter	9
13	Tractor	10
14	Bestelauto (van)	10
15	Vrachtauto (truck)	10
16	Touring car	6
17	Besloten busvervoer (private bus)	6
18	Boot (boat)	10
19	Vliegtuig (plane)	10
20	Kinderwagen (pram)	1
21	Skates/Skeelers/Step	10
22	Gehandicapten vervoermiddel (handicapped transport)	10
26	Anders (others)	10

Table 7 ADB emission factors (left)

Table 8 Dutch emission factors (right)

Modes	Emission Factor (kg/km)
Walking	0
Cycling	0
2w/3w	0.052
Car	0.153
Taxi	0.306
Bus	0.029
BRT	0.022
LRT	0.02
MRT	0.02
Other	0.044

Source: ADB (2010)

Code 1	Modes	Emission Factor (kg/km)
1	Walking	0
2	Cycling	0
3	Small motorcycle	0.059
4	Car driver	0.188
5	Car passenger	0
6	Bus	0.064
7	Tram/metro	0.087
8	Train	0.102
9	Motor	0.136
10	Other	0.044

Source: den Boer, et al., (2008)

Table 9 Modal split of Dutch trips based on MON 2008 sample

Trip modes		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Car driver	42500	30.7	32.3	32.3
	Car passenger	17510	12.7	13.3	45.6
	Train	2426	1.8	1.8	47.4
	Bus/Tram/Metro	3642	2.6	2.8	50.2
	Small motorcycle	858	.6	.7	50.8
	Cycling	33910	24.5	25.7	76.5
	Walking	28994	21.0	22.0	98.6
	Other	1905	1.4	1.4	100.0
	Total	131745	95.3	100.0	
Missing	System	6551	4.7		
Total		138296	100.0		

Table 10 Modal split for all 2008 trips in passenger kilometre travelled (PKT)

Mode	**PKT (Billion km)**	**Percentage (%)**
Car driver	94.9	50.2
Car passenger	48.8	25.8
Train	15.9	8.4
bus/tram/metro	5.9	3.1
Small motorcycle	0.8	0.4
Cycling	13.8	7.3
Walking	4.3	2.3
Other	4.6	2.4

3.2.2.3. Reliability of CVoC model

In each trip bin, the model picks out the cycling trips and estimates their best alternative based on the rest of the trips in the bin. This leads to a question—if the trip maker will still make the trip when cycling is no longer an alternative. To answer this question, the characteristics of the trip should be investigated, especially the trip purposes. Major types of human activities and their sub-types of trips are summarized by Golledge and Stimson (1997). They also reviewed the trips types in terms of their importance and the substitution effects. Work related trips are viewed as the most important trips by planners, while social trips are reported to have some relation with household size and family income (Golledge & Stimson, 1997). According to Cullen and Godson (1975), there are four categories of activities that affect the subjective rating of fixity people may ascribe to activities. They are:

(a) Arranged activities where joint action with other people has been planned and the time and place of the activity are therefore usually fixed

(b) Routine activities which often seem to acquire almost Pavlovian mental and physical associations and which frequently attain the status of virtually immovable points in a person's day. (According to Golledge and Stimson's interpretation (1997), routine activities are undertaken with sufficient regularity and frequency that they may become highly fixed, particularly in time.)

(c) Planned activities which the individual decides to undertake sometime in the future. The degree of flexibility associated with these planned activities may vary widely from a vaguely formulated idea to get one's hair cut this week to an avowed intention to buy a birthday present at lunchtime today. Thus the degree of flexibility attached to planned activities may be greater or less than that of routine or even arranged activities, but would generally be greater. Also interpreted as "the nearer in future time an activity is, the harder it is to adjust its planned space-time location" (Golledge & Stimson, 1997).

(d) Unexpected activities which either 'just happen' as the individual drifts into some pursuit, such as reading a magazine, or which are sprung on a person by chance meetings, accidents, and so on and which have no fixity in a long-term planning horizon but may override all previously arranged or planned activities instantaneously.

Based on these four categories, the trip purposes in the MON survey can be classified. Work and education related trips could be regarded as routine activities which are highly fixed in time and location and there is little chance that the trip maker won't make such trip or change the destination, as is the case with visiting a church. Some work trips (business and meetings), services and personal care (GP or hospital) and visiting friends may be arranged activities. Going to movies, theatres and other cultural and social events might be regarded as planned activities, which are also not easy to change in time and location. The most difficult ones are shopping trips. There are many factors influencing the fixity of shopping trips. Who is making the shopping trip? (The housewife? Or the employee on the way back home?) Is the shopping activity a regular grocery shopping or garments and furniture which might only be found in some large shopping malls? For grocery shopping, the trip maker may have several alternatives around his or her departure location and make his/her decision based on the distance, the price of modes and goods, and other factors. For some specific shopping purposes, the location might be highly fixed. Since there are so many characteristics of shopping trips, their fixity in terms of mode substitution and change of destination is not easy to determine, especially for all shopping trips without revealing any details of the trips from a national survey.

People may not make a trip when cycling is not possible. This is the discouraging effect of removing the transport mode. The trip/no trip dichotomy requires the decision of the trip maker based on three component: the range of possible activities, the set of destination offering suitable facilities for activity participation, the characteristics of available transport system (Golledge & Stimson, 1997).

In summary, the discouraging effect of most non-shopping trips is likely to be very small, meaning that most trip makers would still make their trip—using another mode to the same destination. For shopping trips, the fixity level varies according to the shopping time, what to buy, the departure location and many other factors. Some shopping trips might change their destination or even cancel the trip if cycling is no longer an alternative. For example, an individual who used to cycle to a nearby supermarket will drive to a different place—maybe an even larger supermarket with more choices. In this research, such situation cannot be modelled. However, it is assumed that the trip discourage effect in the Netherlands is very small, simply for the reason that Dutch people have access (physically and financially) to most other transport modes even when cycling is not possible. Though shopping trips might be changed of trip destination, so the distance might be different, it is assumed that on average the change of distance is not significant.

There might be some people drive longer distance to another shopping destination, and also might be some other people who walk to closer places.

Accordingly, the reliability of the model holds good for non-shopping trips and may have some bias for shopping trips, which account for 22.7% of cycling trips, and 15.1% of PKT of cycling (both before extended).

3.2.3. Urban Form Data Preparation

As discussed in the first chapter, three dimensions of urban form information are needed for this research. They are (1) density, (2) diversity, and (3) design. However, constrained by data availability, some of them are hardly possible to acquire for all 443 (in 2008) Dutch cities, especially the land use mix (diversity). Discussion with experts and supervisors broadened the original horizon and focus is given to some urban indicators such as presence of university, train station, etc. The distance to highway and the length and density of cycling infrastructure are derived from the shapefile of roads in The Netherlands which are extracted from CloudMade data using ArcGIS. Though it is possible to calculate population density based on number of inhabitants and the physical area size of the shapefile at hand, it is more accurate to directly use the population density from CBS. Other information such as average density of human activities, average distance to nearest school, GP, hospital, large supermarket, library, cinema, and sports centre are also available from CBS. Such information is helpful to build urban form indicators. For example, the average density of human activities could serve as a trip destination indicator while the multiple distances to different social services are fundamental in understanding the degree of urban land use mix.

4. DATA ANALYSIS, RESULTS, AND DISCUSSIONS

4.1. CVoC — single year modelling

With the 2008 MON database and the CVoC model (described in chapter 3), which was implemented in the mathematical modelling software MATLAB, the CVoC was successfully calculated for 437 out of 443 municipalities in the year 2008. Six municipalities have no results partly due to their very small sample size, and were left out. They are Vlieland, Rozendaal, Andijk, Graft-De Rijp, Bennebroek, and Zeevang. The number of samples for these cities is under 20 per municipality in the year of 2008. In the modelling, the original modes are reclassified to 10 modes (see table 4 in section 3.2.2.1) with Dutch emission factors (see table 6 in section 3.2.2.2) from the CE-DELFT report (den Boer, et al., 2008). The emission factors for public transport are calculated based on the average ridership of the Dutch public transport (den Boer, et al., 2008). The trip bin size is set as 2 km, and the upper limit trip distance is 20 km, above which there are only 0.8% of cycling trips (see table 5 in section 3.2.2.2). The following indicators are calculated for each municipality: (1) Total CVoC: Total induced emissions of carbon dioxide for the study area based on all substituted cycling trips; (2) Per capita CVoC: Total CVoC divided by the population of the study area; (3) Unit CVoC: Total CVoC divided by the total cycling trip distance; and (4) CVoC density: CVoC per square kilometre land area.

Table 11 Top ten municipalities in terms of total CVoC (single year modelling)

Name	**Population**	**Total CVoC per year [tons CO_2]**	**CVoC per capita per year [kg CO_2]**	**Bicycle Passenger Kilometre Travelled (PKT) per capita per year [km]**	**Total Bicycle PKT per day [km]**	**Average cycling distance per person per day [km]**	**Cycling share in modal split [%]**
Amsterdam	747,090	55250	74	937	1918776	2.57	21
Utrecht	294,740	31089	105	1,175	949207	3.22	21
's-Gravenhage	475,680	27910	59	682	889248	1.87	17
Groningen	182,480	26823	147	1,617	808249	4.43	36
Rotterdam	582,950	25798	44	477	761057	1.31	13
Eindhoven	210,330	24718	118	1,227	706879	3.36	25
Tilburg	202,090	18359	91	792	438565	2.17	24
Zwolle	116,360	17944	154	1,406	448136	3.85	34
Nijmegen	161,250	15845	98	1,010	446337	2.77	20
Breda	170,960	15538	91	838	392493	2.30	24

The flows are the result of the interaction between land use and transport (Manheim, 1979). In this research one type of flows – cycling trips are studied. Cycling performance will be different in different urban systems with different configuration of urban land use and transport, thus making their climate value different. It is interesting that Rotterdam and Den Haag, though highly urbanized, with large population, many human activities, short distances between destinations, and good provision of cycling infrastructure, their cycling share in modal split is comparatively lower than most other highly urbanized municipalities, and their per capita CVoC are also lower than municipalities like Amsterdam and Utrecht, which are the other two in the "big four".

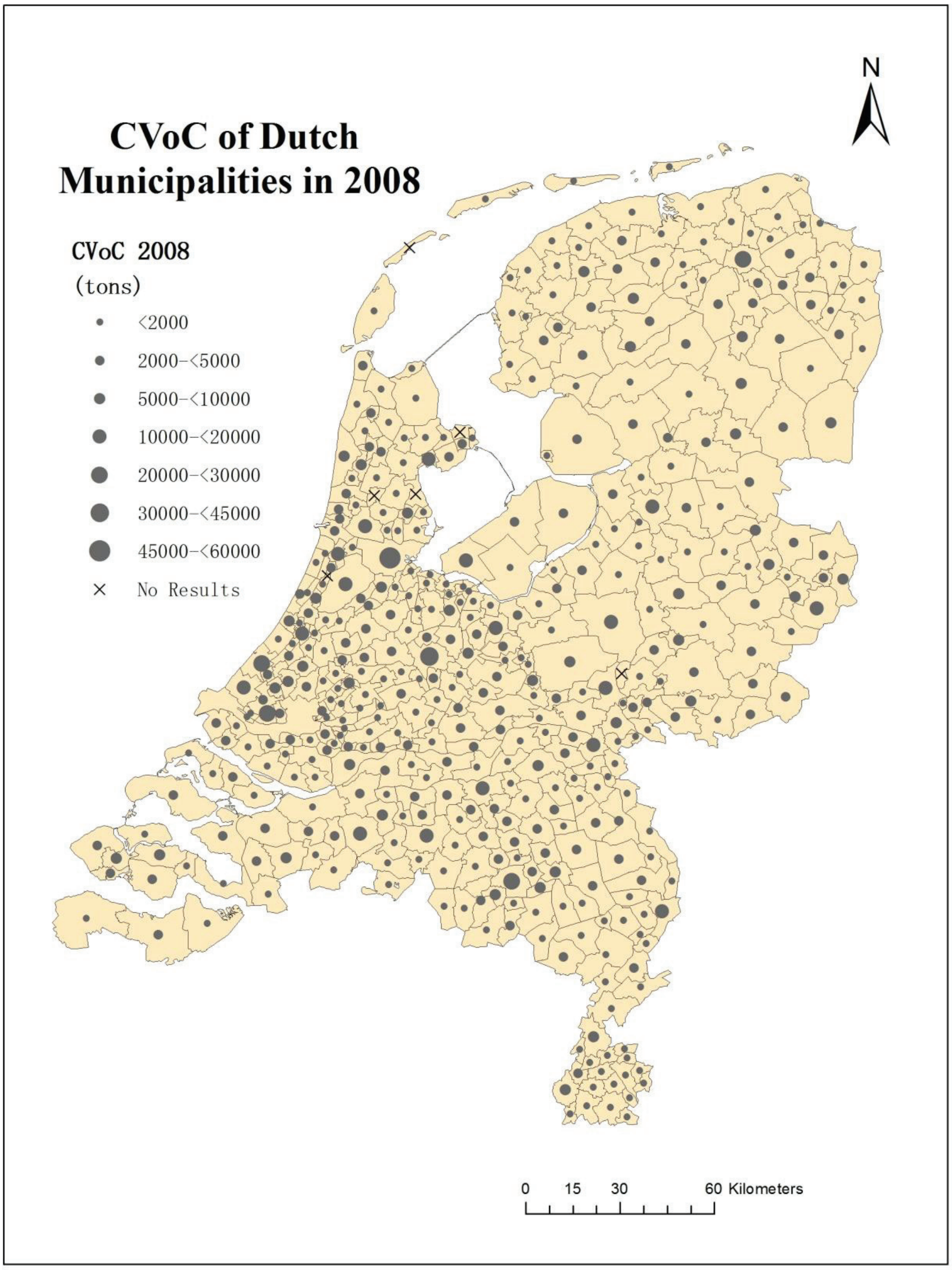


Figure 7 Total CVoC of Dutch municipalities in 2008

The total CVoC presents the aggregated climate value that cyclists create in one year. As shown above in figure 7, municipalities on the western coast (as is known they are much more populated) have larger symbols since they also have more cyclists based on their population. The total CVoC for each municipality could be further aggregated to see how much emission the whole country saves in a year through its cycling trips. However, local governors may be more interested to know how much emission is avoided by their cyclists. They may ask for fund from the national government based on their CVoC level for further endeavours of mitigating climate change in the transport sector.

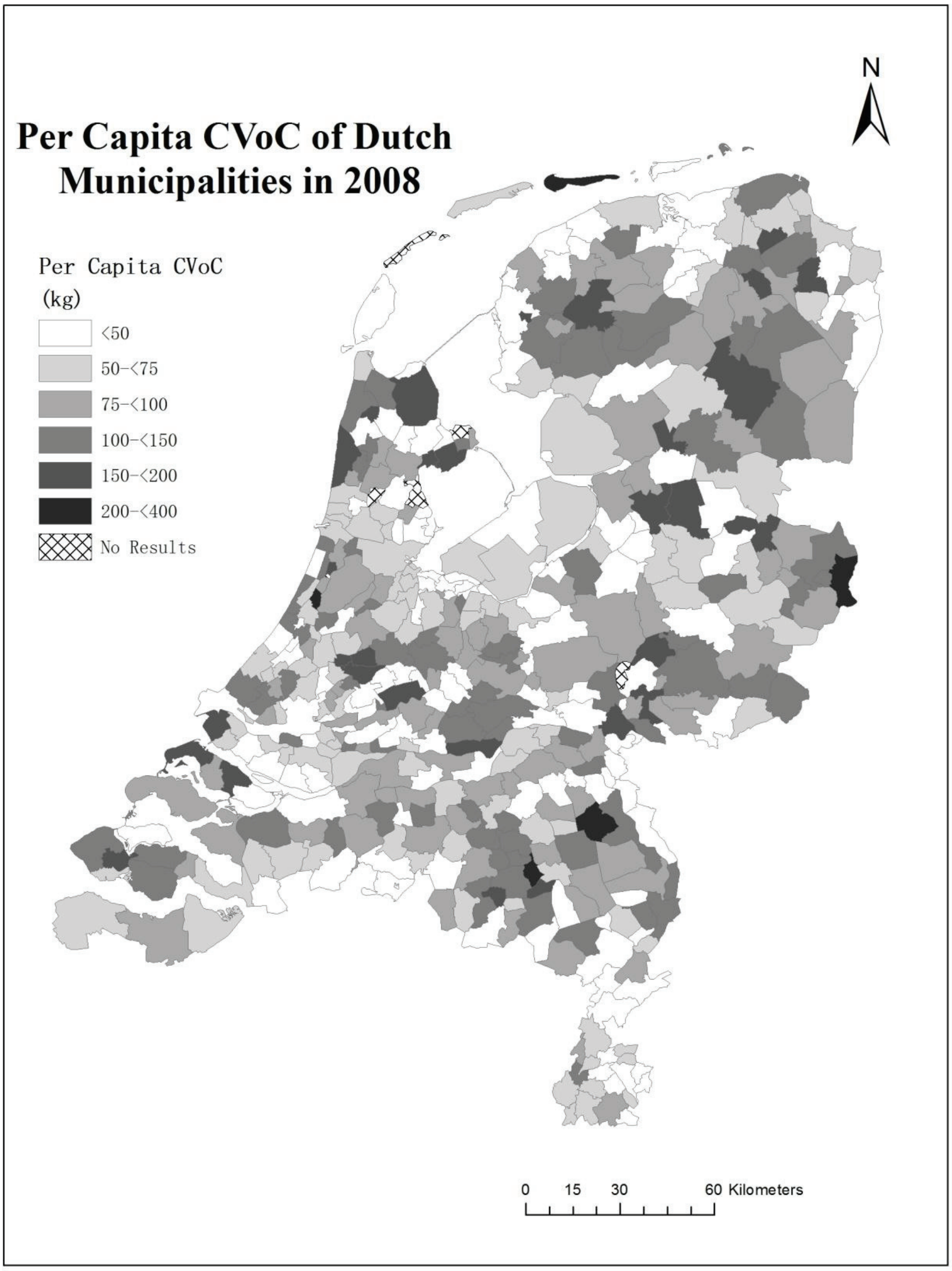


Figure 8 Per capita CVoC of Dutch municipalities in 2008

Per capita CVoC quantifies the climate value each individual creates on average in one municipality. If in one municipality every one tends to cycle more trips and distances, they together would create a larger per capita CVoC and make the municipality darker in figure 8.

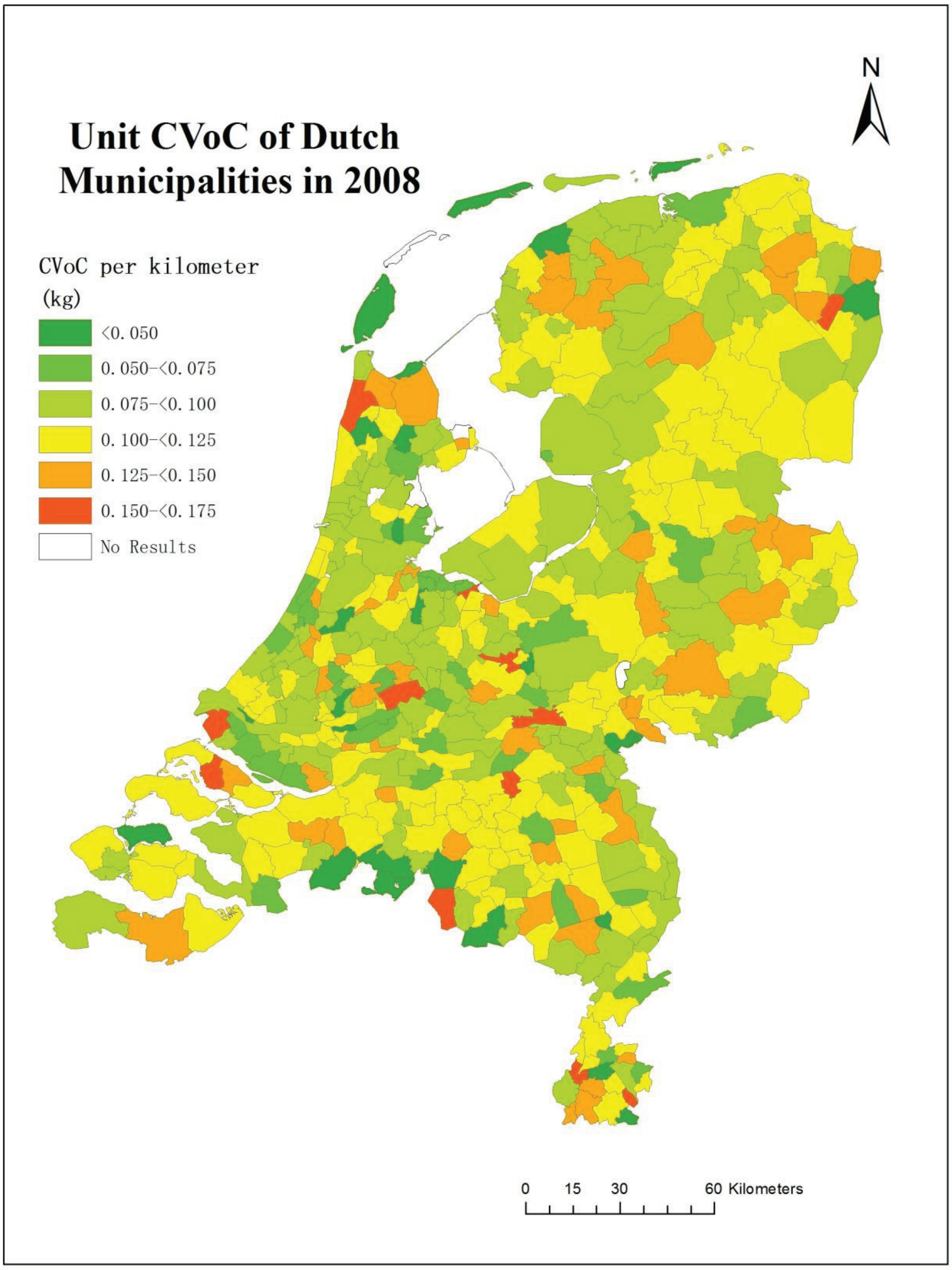


Figure 9 Unit CVoC of Dutch municipalities in 2008

Mapped in colour, Unit CVoC is intended to show the level of sustainability of the transport system, excluding cycling. Apparently from the map, one kilometre cycling in different municipalities has different climate value—it equals more emissions in reddish municipalities than in green municipalities. This is because their transport systems are different, which would affect the substitution mode. Increasing the cycling performance in more reddish areas would create more climate value and making their transport system more sustainable.

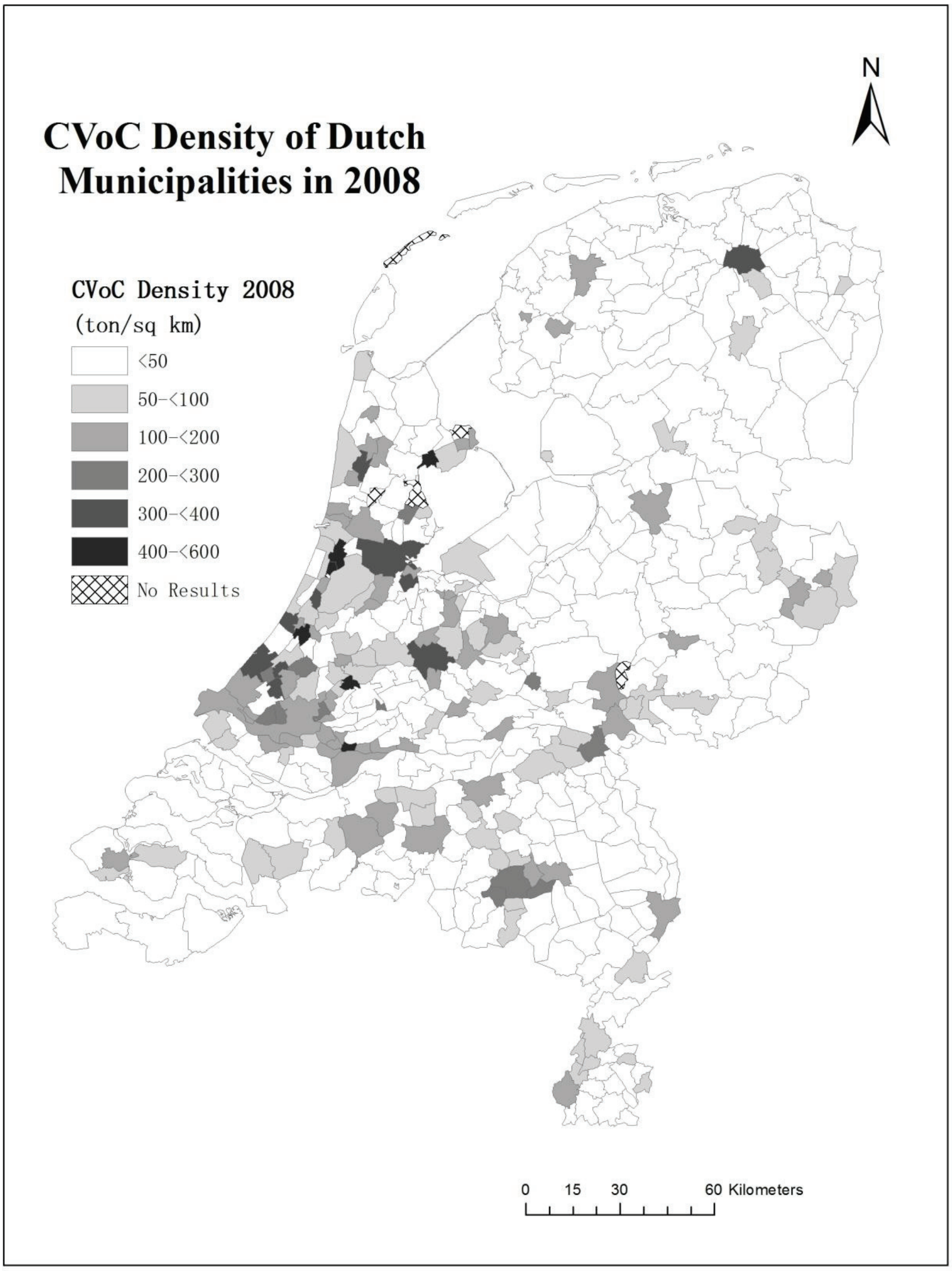


Figure 10 CVoC density of Dutch municipalities in 2008

The CVoC density depicts the intensity of climate value on a land unit. Municipalities with higher population and activity density would appear darker on the map, indicating an intensive cycling use. So the climate value created would be larger in each square kilometre land.

4.2. CVoC — average of multiple years

The Climate Value of Cycling for Dutch municipalities previously modelled is based on the single year data MON 2008, in which some municipalities have very a limited number of observations (recorded trips). This is also the reason why six municipalities have no results. Basically, the trip makers in the MON are expanded to the whole Dutch population, based on their characteristics such as gender, age, income, etc at the province level. More specifically, the expansion factors are weighted by considering the following aspects: urbanization, province, age group, household size, fill-month, sex, year of the car, fuel, age class of the car, and the owner of the car (Ministry of Transport, 2010). The trips by the trip maker are then expanded simply by the multiplication of 365 (with a correction for holidays) and the expansion factor of person, assuming those people have similar travel behaviour. However, limited observations of people and trips would make the expansion factor for them very large and less accurate. Since the CVoC modelling in section 4.1 is based on one year data, some municipalities have more observations than others. For municipalities with a large amount of observations, this might not be a problem. However, some municipalities with few records may have distorted CVoC simply because the interviewees were too few and they were not representative enough. A large number of observations would cover a variety of people and trips so they are more representative. In order to have more observations for each municipality, the MON 2004 to 2009 are stacked together to render more observations, approximately 1.1 million records. However, the number of municipalities (also their names) from 2004 to 2009 changed year by year. Each year, some municipalities were merged and renamed as another or named as the dominant municipality. The administrative changes of the municipalities are recorded on CBS websites (CBS, 2005, 2006, 2007, 2009a). Overall speaking, 483 municipalities in 2004 were reorganized into 441 municipalities in 2009. In order to keep the 6 years' data comparable and matching, transformation of the codes of municipalities is carried out for the stacked MON data. All the "old municipalities" are re-coded by their new codes and names according to the information in the above mentioned website. Due to the limited memory of Matlab, the transformation is finished by using Python. Previously there were 6 municipalities with no results for CVoC, this problem is now solved since by stacking 6 years' observations, their CVoC could be modelled.

In this round, the stacked MON data 2004-2009 is used and the result of climate value of cycling is then the average of the 6 years. For some municipalities, which had very limited number of observations in a single year, their values of CVoC are better estimated with the stacked MON data. This is because of the increased sample size for each municipality, which made the modal split in each trip bin more representative of the real situation. Originally by using one year data (MON 2008), some municipalities only had very limited sample trips, which did not cover the range of transport modes for the trips made in the municipalities. Their unit CVoC and per capita CVoC are then somehow biased and could not represent the real situation. The average value of CVoC based on six years' observation solved this problem. The results of per capita CVoC and Unit CVoC are in a much narrower range, which means the differences among Dutch municipalities are smaller than the results generated in section 4.1.

4.2.1. Total CVoC for each municipality

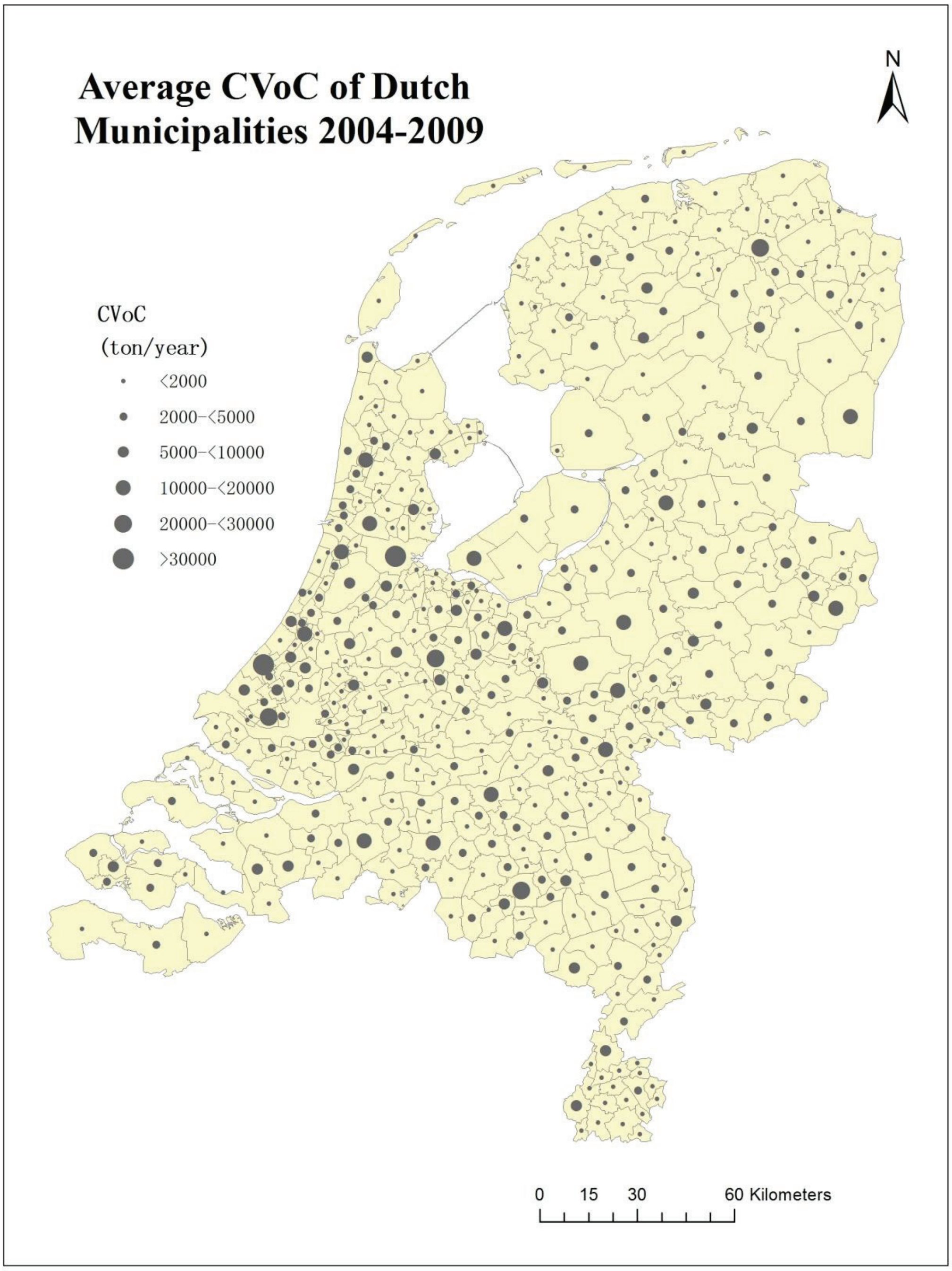


Figure 11 Average total CVoC of Dutch municipalities 2004-2009

A municipality with a high CVoC should have a large amount of cycling PKT, which is mostly based on the number of cycling trips, since the cycling trips on average have a short distance. On the map, municipalities with bigger symbols suggest that more trips are realized by cycling. For example, Amsterdam has more than 0.6 million cycling trips in a single day, which are more than twice that of Den Haag and Rotterdam. This makes Amsterdam the highest in CVoC in the Netherlands, with 61654 tons of CO_2 saved each year on average from 2004 to 2009. However, for two municipalities with similar cycling PKT, their CVoC might be different. For example, Hengelo has fewer cycling PKT than Haarlemmermeer, but its CVoC is higher. This could be explained by the competition effect of the rest of the transport system. The competition effect, i.e. which mode will replace the original cycling trip, can lead to difference of CVoC since their emissions are different. For every kilometre travelled, private cars have twice more emission on road than the average public transport (train, tram/metro, and bus). This effect would be presented and explained in detail in the part of Unit CVoC.

Table 12 Top ten municipalities in terms of total CVoC (2004-2009 average)

Name	**Population (2009)**	**Total CVoC per year [tons CO_2]**	**CVoC per capita per year [kg CO_2]**	**Bicycle Passenger Kilometre Travelled (PKT) per capita per year [km]**	**Total Bicycle PKT per day [km]**	**Average cycling distance per person per day [km]**	**Cycling share in modal split [%]**
Amsterdam	755610	61654	81.60	996	2062815	2.73	22
Den Haag	481860	30545	63.39	723	954083	1.98	17
Rotterdam	587130	29960	51.03	577	927665	1.58	15
Utrecht	299890	25273	84.27	975	800706	2.67	23
Groningen	184230	23297	126.45	1398	705601	3.83	33
Eindhoven	212270	23147	109.04	1080	628319	2.96	25
Breda	171920	19339	112.49	1059	498568	2.90	24
Apeldoorn	155330	18962	122.08	1212	515696	3.32	30
Nijmegen	161820	18585	114.85	1190	527533	3.26	26
Tilburg	203460	17072	83.91	821	457785	2.25	24

The table above lists the top ten Dutch municipalities regarding their total CVoC in a single year. Together, Dutch people avoid 1.36 million tons of CO_2 each year simply through cycling. This amount of avoided emission is based on a daily cycling trips of 12.9 million and daily cycling PKT of 38.7 million km. However, this figure may seem far away from them since most people have no idea how much CO_2 that is. A high school teacher in the U.S. built a large cube that represents the size of 1 ton CO_2 in 2008, which is about 27 feet high by 27 feet wide by 27 feet deep (557 m^3) (Energyrace, 2008). Directly, 1.36 million of such cubes of CO_2 are avoided by Dutch cyclists in a single year. From another perspective, if all the avoided CO_2 is emitted, the Dutch people need the equal number of trees to absorb such amount of CO_2 in their life time[1]. However, the avoided emission is only for one year. So if suddenly all cycling trips are substituted by other modes, The Netherlands need 54.4 million trees to absorb the CO_2 emission originally saved by cycling in a single year. If these avoided emissions are monetized, according to the European Union's Emission Trading System, 1.36 million tons of CO_2 equals 54.4 million (EUR) which is calculated for the first phase of the penalty level (€40 per ton CO_2)(Wals & Rijkers, 2009).

However, each Dutch municipality does not contribute equally to the climate value of cycling according to their population. Below is the list of top 30 (by population) Dutch municipalities with their share in population and CVoC. With a negative net C-P value (share of CVoC minus share of population) (see figure 12), municipalities such as Rotterdam, Den Haag, Almere, etc have poorer cycling performance.

[1] Accepted by NASA and Kyoto Protocol, 1 tree absorbs on average 1 ton of CO_2 over its lifetime. This calculation is based on the absorption figure that on average 1 tree absorbs 24 kg of CO_2 per year and the average lifetime of a tree is 40 years (Ecoswitch, 2009).

Table 13 Share of population and CVoC of the national total, top 30 municipalities

Municipality	Share of Population (%)	Share of CVoC (%)
Amsterdam	4.58	4.53
Rotterdam	3.56	2.20
's-Gravenhage	2.92	2.24
Utrecht	1.82	1.85
Eindhoven	1.29	1.70
Tilburg	1.23	1.25
Almere	1.13	0.82
Groningen	1.12	1.71
Breda	1.04	1.42
Nijmegen	0.98	1.36
Enschede	0.95	1.04
Apeldoorn	0.94	1.39
Haarlem	0.90	0.90
Arnhem	0.88	0.81
Zaanstad	0.87	0.82
Amersfoort	0.87	1.17
Haarlemmermeer	0.86	0.64
's-Hertogenbosch	0.84	0.77
Zoetermeer	0.73	0.65
Dordrecht	0.72	0.65
Maastricht	0.72	0.64
Zwolle	0.71	1.21
Leiden	0.71	0.86
Emmen	0.66	0.74
Ede	0.65	0.76
Westland	0.60	0.72
Deventer	0.59	0.62
Delft	0.59	0.63
Sittard-Geleen	0.58	0.56
Leeuwarden	0.57	0.66

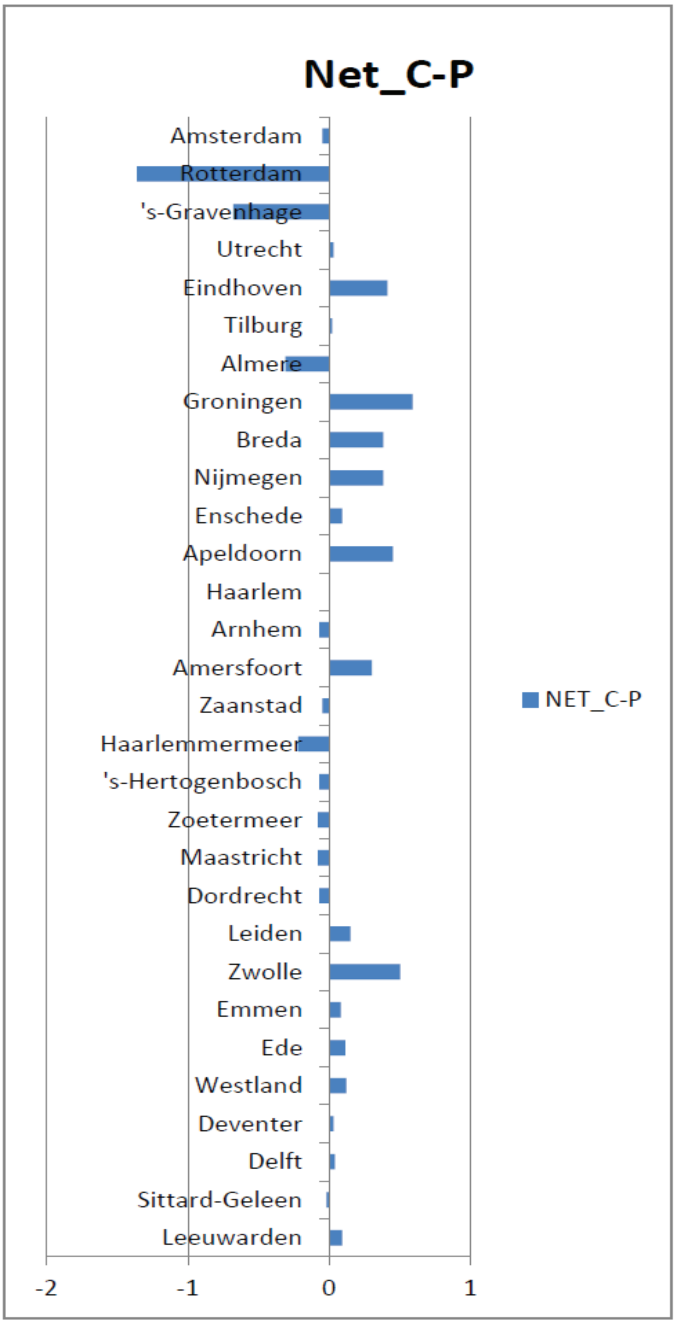


Figure 12 Net value of share of CVoC minus share of population

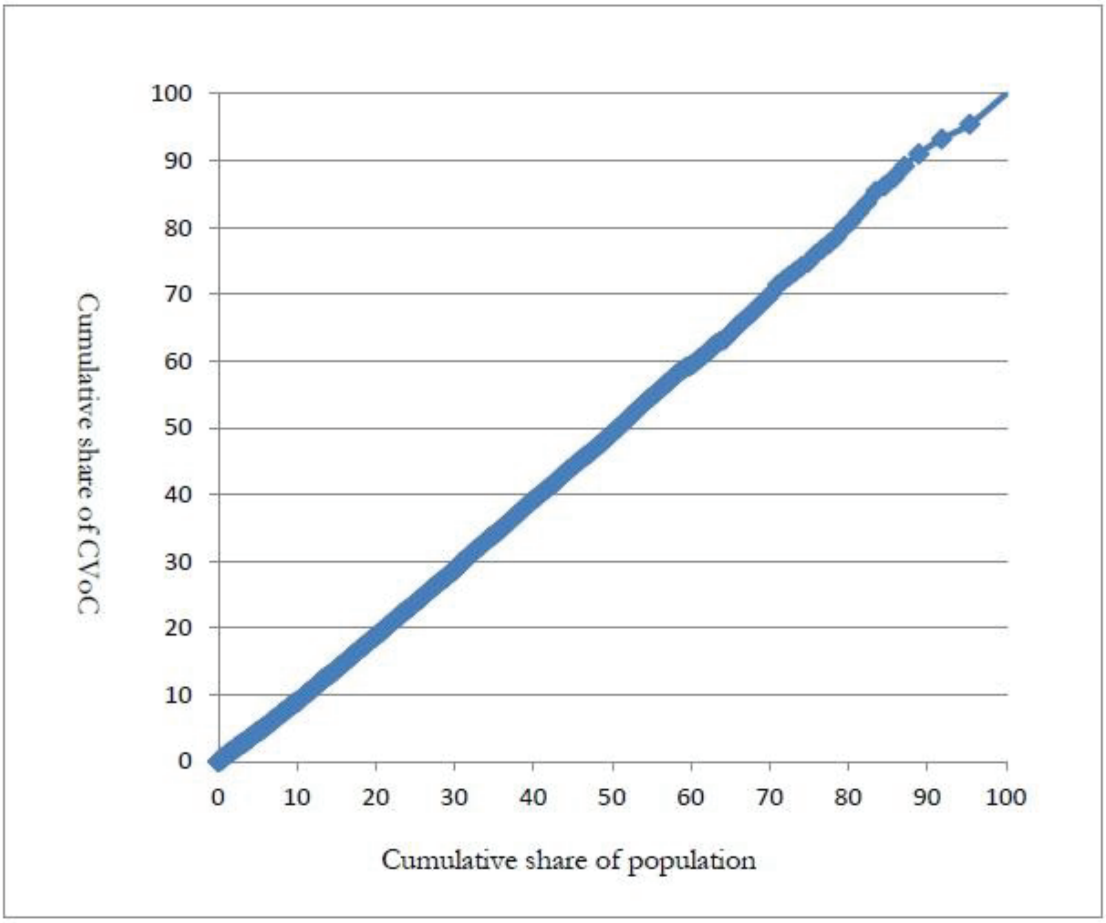


Figure 13 Lorenz curve for CVoC VS population in The Netherlands

Obviously, cycling performance is better in municipalities whose share of CVoC is larger than its share of population, and vice versa. Here are some examples. Rotterdam only contributes 2.2% of CVoC though it has a population of 3.56% of the total. Eindhoven, Apeldoorn, and Zwolle, on the other side, generate significantly more CVoC based on their population.

Overall speaking, the climate value of cycling is distributed quite equally among Dutch municipalities, as can be seen from the graph above—the 441 municipalities are located almost exactly along the equality line (0, 0 to 100, 100).

On average, each Dutch citizen contributes 82 kg of CVoC each year. However, the variation among municipalities for this figure is quite big, with the lowest less than 10 kg and the highest reaching 200 kg. The next map will show the per capita CVoC for each Dutch municipality.

4.2.2. Per capita CVoC for each municipality

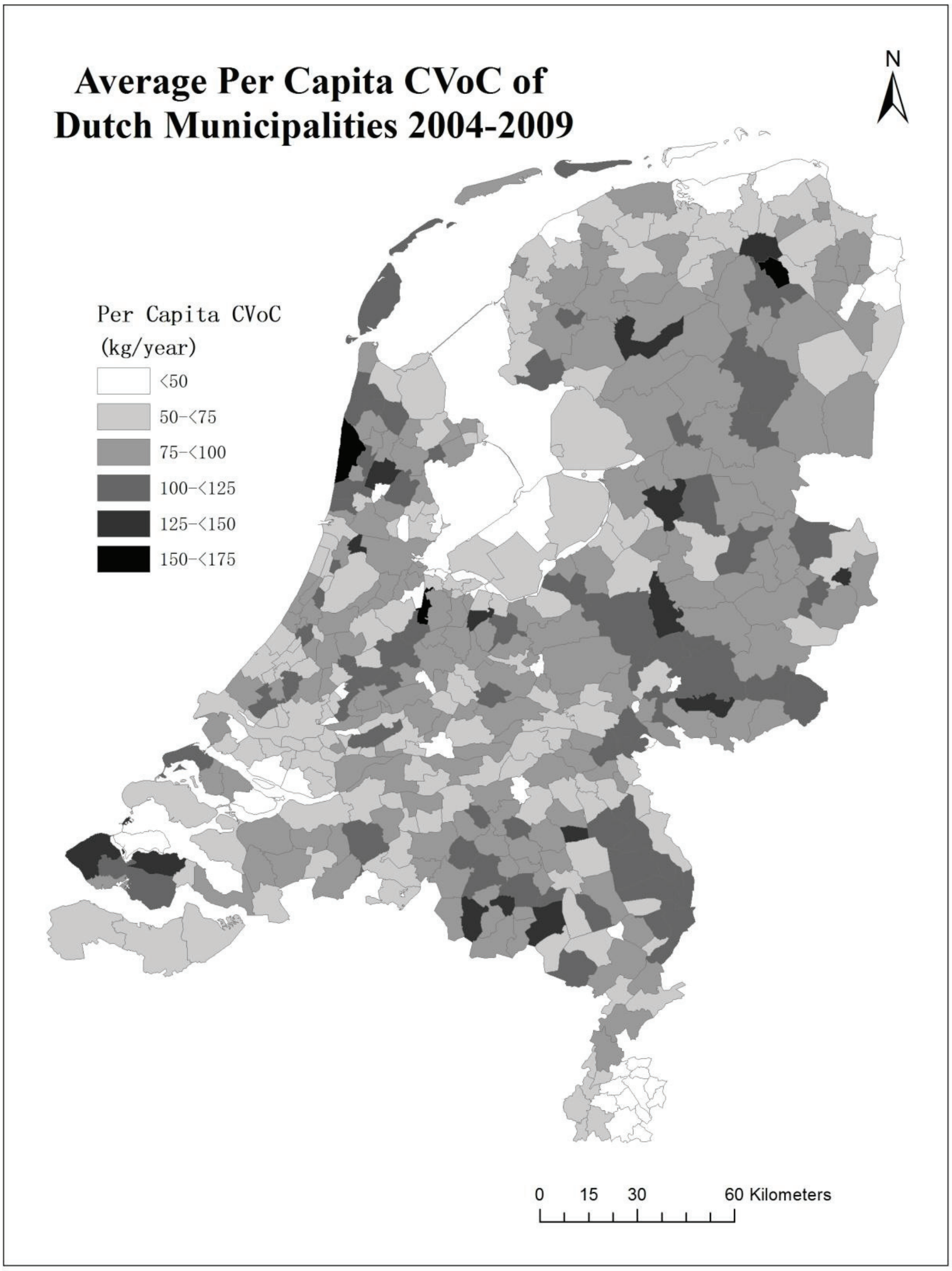
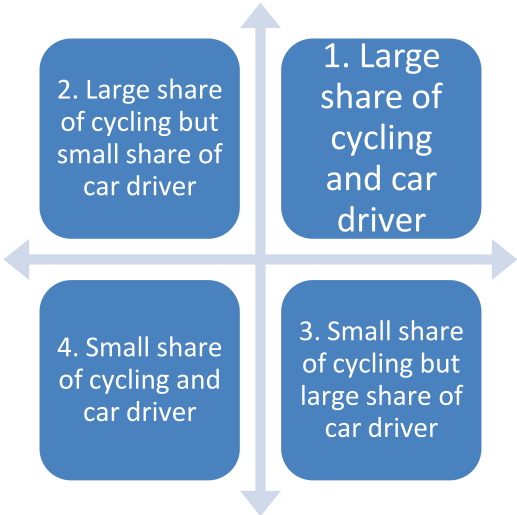


Figure 14 Average per capita CVoC of Dutch municipalities 2004-2009

By dividing the total CVoC per municipality with its population, it is possible to see the contribution from the individual. The municipality with the highest value of per capita CVoC (162 kg/year) goes to Loenen (GM0329). Taking it as example, on the one hand, municipalities with high per capita CVoC should have a large share of cycling trips—usually above 30%, and the average distance by cycling per capita would also be long—more than 3 kilometers. On the other hand, such municipalities also have large share of private cars and the share of walking, public transport are both low. So that when cycling trips are substituted, they are more likely to be replaced by highly emitting modes, which will make the CVoC even higher.

Municipalities with low per capita CVoC have fewer cycling trips and shorter distance. They may also have large share of walking and public transport.



Modal share: both in terms of trips and PKT. Per capita CVoC: 1>2>3>4.

Figure 15 Types of Dutch municipalities by modal share difference

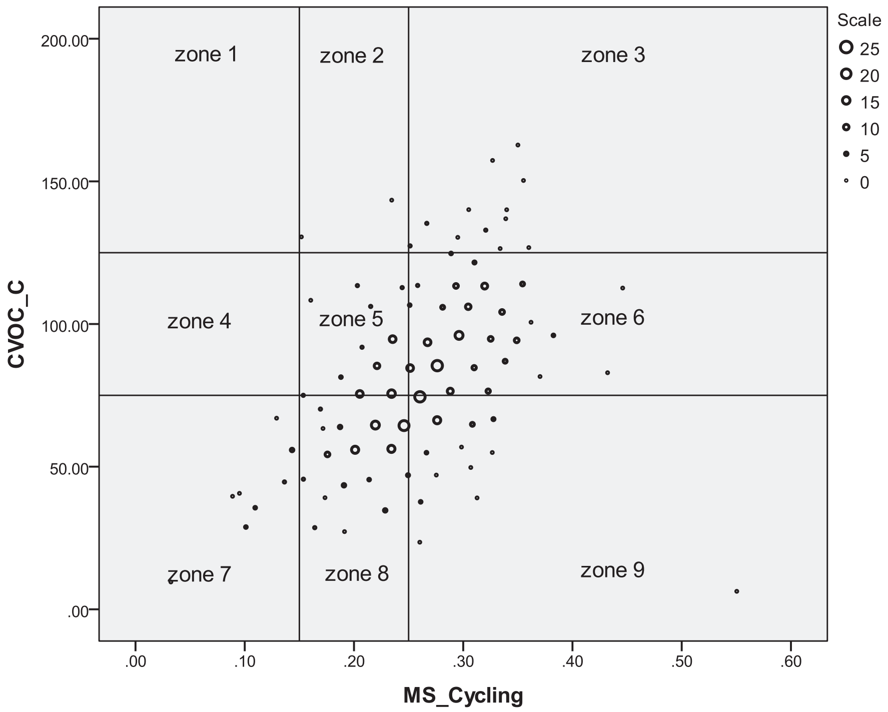


Figure 16 Scatter plot of cycling share and per capita CVoC for Dutch municipalities

In order to have a better understanding of per capita CVoC, the Dutch municipalities are plotted based on their per capita CVoC and modal share of cycling. For each variable, two cut-off values are used to differentiate between low, medium, and high level. The cut-off values for per capita CVoC are 75 kg and 125 kg; while the cut-off values for modal share of cycling are 15% and 25%. So, as plotted, zone 1, zone 4, and zone 7 have a low share of cycling, with zone 2, zone 5, zone 8 a medium level, and zone3, zone6, zone 9 a high modal share of cycling. Similarly, zone 1, 2, 3 have high per capita CVoC, with zone 4, 5, 6 medium level, and zone 7, 8, 9 the lowest level. The municipalities which are very close to each other are merged by bigger circles for a better visualization, since 441 municipalities would make the graph very crowded, especially between the area (zone 5, 6, 8 and 9) where most Dutch municipalities show similar values in terms of per capita CVoC and modal share of cycling.

Table 14 Categorizing Dutch municipalities using cycling share and per capita CVoC

	Low MS_Cycling (<15%)	Medium MS_Cycling (15%-25%)	High MS_Cycling (>25%)	SUM
High CVOC_C (>125 kg)	0 (zone 1)	3 (zone 2)	15 (zone 3)	18
Medium CVOC_C (75 kg-125 kg)	0 (zone 4)	61 (zone 5)	176 (zone 6)	237
Low CVOC_C (<75 kg)	17 (zone 7)	111 (zone 8)	58 (zone 9)	186
SUM	17	175	249	441

Overall speaking, there is a significant correlation between modal share of cycling and per capita CVoC—the higher the cycling share, the higher level of per capita CVoC. The Pearson correlation is .535 at the significance level of 0.01 (two-tailed).

As classified in the table, the majority of Dutch cities have a high to medium level of cycling—there are 249 municipalities with a cycling share of more than 25% and 175 municipalities with more than 15%. However, only 18 municipalities reach the high level of per capita CVoC (125 kg/year). The majority stays in the category of medium to low per capita CVoC. This is because of the comparatively short distance of cycling trips in these municipalities.

For the 17 municipalities with a low level of cycling (below 15%), only Rotterdam is a major municipality with good performance of public transport (16%). It also has a low share of car drivers (22%) compared with the other municipalities, most of which are around 40%. Hence, there is plenty of room for these municipalities to grow in cycling trips.

Many big municipalities fall in the medium level of cycling modal split (15%-25%), for example, the Big Four (except Rotterdam), Eindhoven, Tilburg, Almere, etc. On average, people in these 175 municipalities cycle 1.9 km every day and the average share of car drivers are still high—35%. There is room to reduce motorized vehicles and increase the share of cycling furthermore.

There are 249 out of 441 (56.6%) municipalities with a cycling share of more than 25%, which can never be found in other countries in the world. People in these municipalities cycle 2.6 km every day and create a climate value of 90 kg per year. Typical municipalities in this category are Groningen, Nijmegen, and Enschede. Some of them still have room to increase cycling, if the motorized vehicle in modal split is also high—which means there is room to decrease motorized vehicles by increasing cycling in modal split. Others with specifically high cycling level are facing the problem of maintaining this level.

Combined with per capita CVoC, a detailed interpretation is provided in the following table.

Table 15 Policy responses to different categories of municipalities

CVoC per Capita	Cycling modal share	Interpretation and potential policy response
High	High	These cities, although doing well in terms of cycling modal share are facing a high risk of increased CO2 emissions in case cycling levels cannot be maintained. If, however, they succeed to increase cycling modal share even further, high values of CO2 emissions can be avoided.
High	Medium	Fewer people are making longer trips in combination with a transport system that offers less sustainable alternatives. This combination occurs not very often, only in a few smaller and more rural municipalities. Policies should address the increase of modal share for cycling while at the same time creating more sustainable transport options for longer trips.
Medium	High	Cycling distances are comparatively shorter than in the case of the high per capita CVoC group; 176 municipalities have this combination and what they need is to maintain the high cycling level and create more sustainable transport options.
Medium	Medium	A significant amount of trips are realized by cycling with considerable distances. If cycling rate could be increased further, they would enter the category of High-High.
Low	High	A low risk situation where we have mostly a combination of many short distance cycling trips and sufficiently sustainable alternatives. Policies should be directed at maintaining the current status, or even improving the modal share of cycling further.
Low	Medium	Cycling trips are done in short distances and the alternatives are more sustainable. However, more cycling trips should be encouraged in such municipalities.
Low	Low	A situation where there are opportunities for the use of cycling to grow, preferably while keeping the performance of the other transport modes as green as possible. Usually characterized by short trip lengths, not necessarily by sustainable substitution modes

4.2.3. Unit CVoC for each municipality

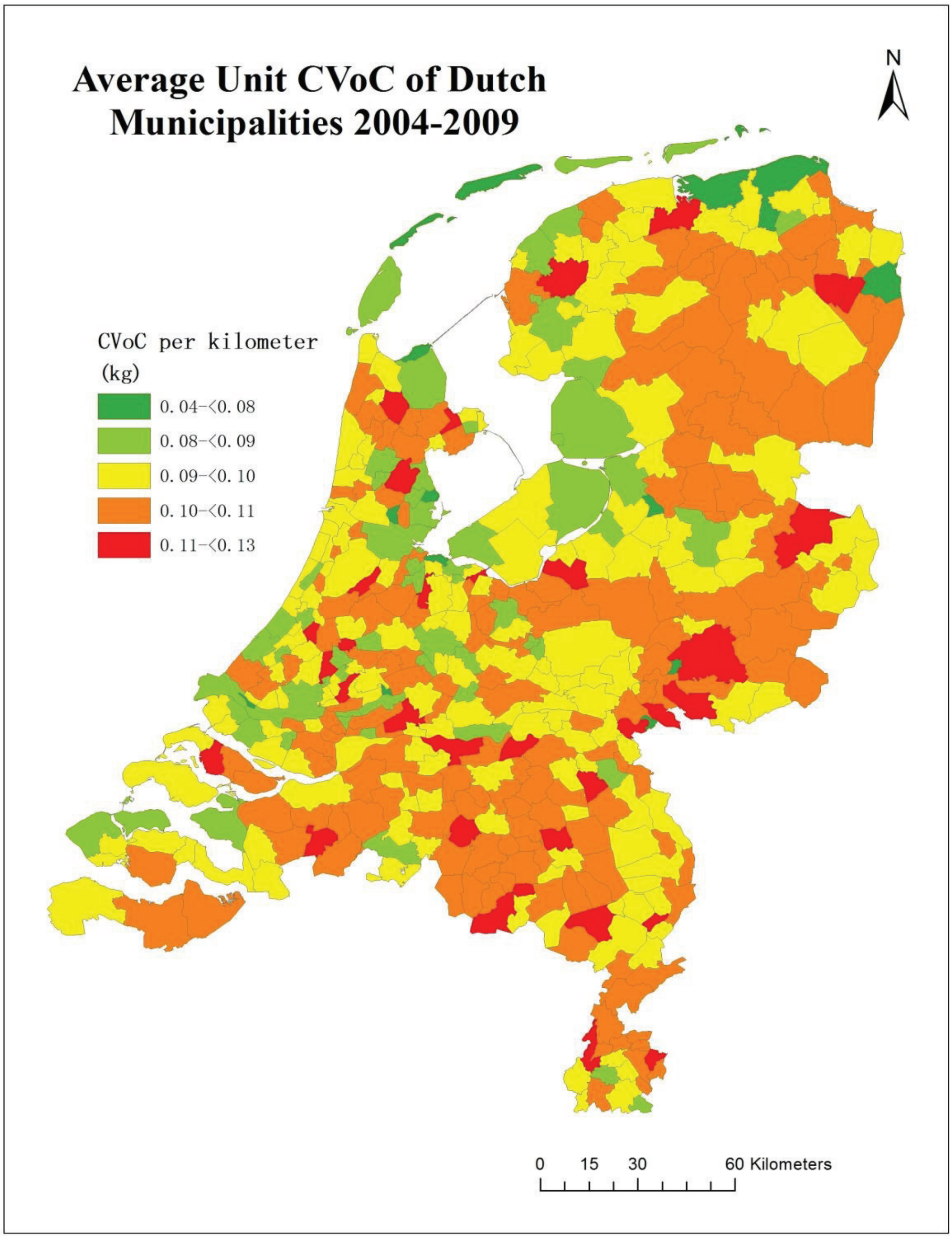


Figure 17 Average unit CVoC of Dutch municipalities 2004-2009

Unit CVoC is an indicator of the competition effect. When removing cycling from the choices of transport modes, the trip maker will choose from the rest of the means. The choice between private cars (as a driver, or a passenger), public transport (bus, metro/tram), and other means (walking…) is called the competition effect. In the model, such effect is decided based on the most frequently chosen mode in the trip bin. The average Unit CVoC represents how much CO_2 emission per cycling kilometre equals in a specific municipality. A low unit CVoC indicates that on average the cycling trips are more likely to be substituted by non-emission and low emission means such as walking, car passenger, and public transport. A high unit CVoC on the other hand suggests that in the municipality cycling trips are more likely to be substituted by private cars (driver). In municipalities with more trips on foot or public transport, the unit CVoC would be lower; otherwise the unit CVoC would be higher where the share of private cars is dominant.

The unit CVoC simply splits the concept of climate value of cycling into two parts: the cycling performance and the substitution mode. As we have known, the total CVoC of one municipality is the result of cycling performance (PKT) multiplied by its unit CVoC. If there is no significant change for the emission factors of the Dutch transport system, such as the increase of the ridership of public transport (which will lead to a decrease of its emission factor) and the technology innovation of private cars or energy (which will also lead to a decrease of its emission factor), the unit CVoC for each municipality would maintain its stability for future estimation. Given the projected performance of cycling (PTK) in the future, it is possible to estimate the CVoC for the target year. To use the unit CVoC for future estimation it is also assumed that people's preferences towards transport modes in each trip distance bin do not change significantly.

Overall speaking, the average unit CVoC is the result of both transport modes (emission) and people's preferences among them. To decrease the unit CVoC is a topic that planners and policy makers should consider besides increasing the cycling performance both in terms of trips and kilometres. Currently, decision makers and planners should keep and/or increase the cycling performance in municipalities with a high Unit CVoC, since they are at the frontier of risk—bringing more emissions when losing cycling.

4.2.4. CVoC Density for each municipality

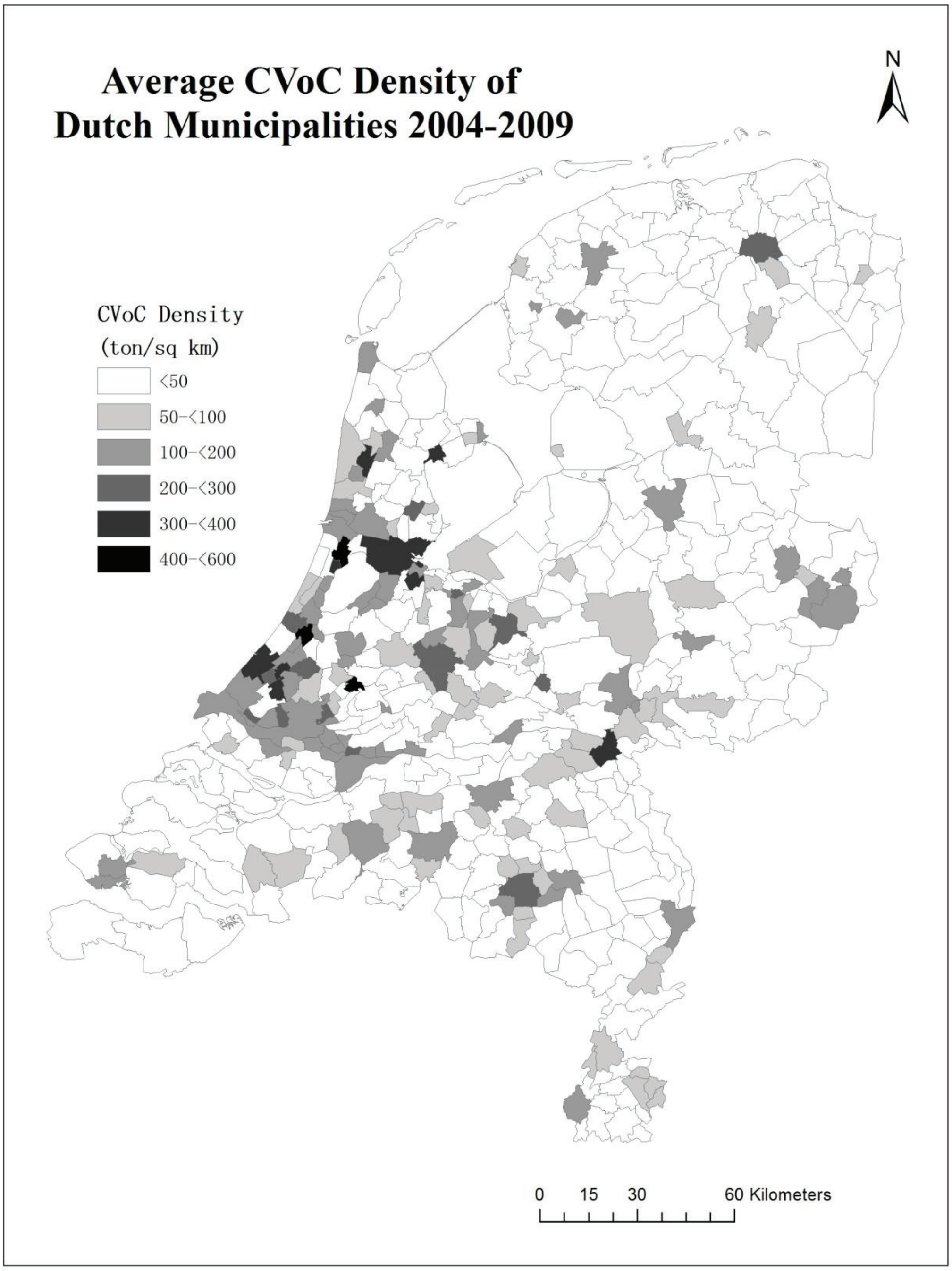


Figure 18 Average CVoC density of Dutch municipalities 2004-2009

The CVoC density depicts the distribution of CVoC on the land area of each municipality. High value municipalities are expected to have high level of urbanization, high population density, and dense concentration of human activities. That's why this map looks very much alike with the map of population density.

4.3. Major urban form indicators

Dutch municipalities show considerable variations in terms of urban form in each dimension. Such differences reflect the planning and economic goals that they choose to implement in the long term. Without policies to encourage compact city development, urban sprawl in the Netherlands between 1970 and 2000 would have been much greater (Mehrotra, et al., 2011). Referring to literature, a city's urban form determines the location of emission sources and the pattern of urban traffic (Dulal, et al., 2011). The physical configuration of the built environment (Anderson, et al., 1996), i.e. dispersed versus compact (Frenkel & Ashkenazi, 2008), the extent and pattern of its open space (especially streets) (Cervero & Kockelman, 1997), and the distances between destinations (Grazi & van den Bergh, 2008) are important factors which could constrain transport options in the specific urban environment. In general the built environment contributes significant amount of GHG emissions – from the buildings and the streets. Emissions from the streets are the result of the interaction of between land use and transport (Manheim, 1979), which of course will create influence on climate change. Though the urban form of each municipality is relatively fixed in the short term, future modification through urban planning and management is expected. It is argued that managing the size and shape of the urban form through land use planning may provide opportunities for climate change mitigation. Similarly, land use control can modify the urban settlement through urban redevelopment (Blanco et al., 2011).

After the literature review, three dimensions (3D—density, diversity, and design) of urban form are summarized as helpful in understanding urban transport explaining the pattern it takes (Cervero & Kockelman, 1997). In this section major urban form indicators are quantified and mapped for Dutch municipalities from the three dimensions..

Table 16 Major urban form indicators

Urban form dimension	Indicator	Explanation
Density	Population Density	Number of inhabitants per square kilometre land
	Density of Human Activities	For all addresses, the average number of human activities within one square kilometre area
	Level of Urbanization	categorical, from 1 (very urbanized, more than 2500 addresses per square kilometre) to 5 (non-urban, less than 500 addresses per square kilometre)
Diversity	Equal Distance	Average distance to the nearest activities of different purposes, including GP/hospital, school, restaurant, large supermarket, library, cinema, and sport centre
Design	Cycling Infrastructure Density	The length of cycling path on one square kilometre land

Table 17 Other urban form indicators

Indicators	Explanation
Transport Node	If the municipality has an inter-city train station
Presence of university	If the municipality has university
Length of cycling path	Total length of cycling path in the municipality
Per capita cycling density	Length of cycling path per inhabitant
Distance to highway	The distance from the centre of the municipality to the nearest highway
Distance to main road	Average distance of all residents to the nearest main road

Table 17 lists other indicators that have been prepared for this study. Limited by the scope of this research, these indicators, however, were included in further discussion.

4.3.1. Population Density

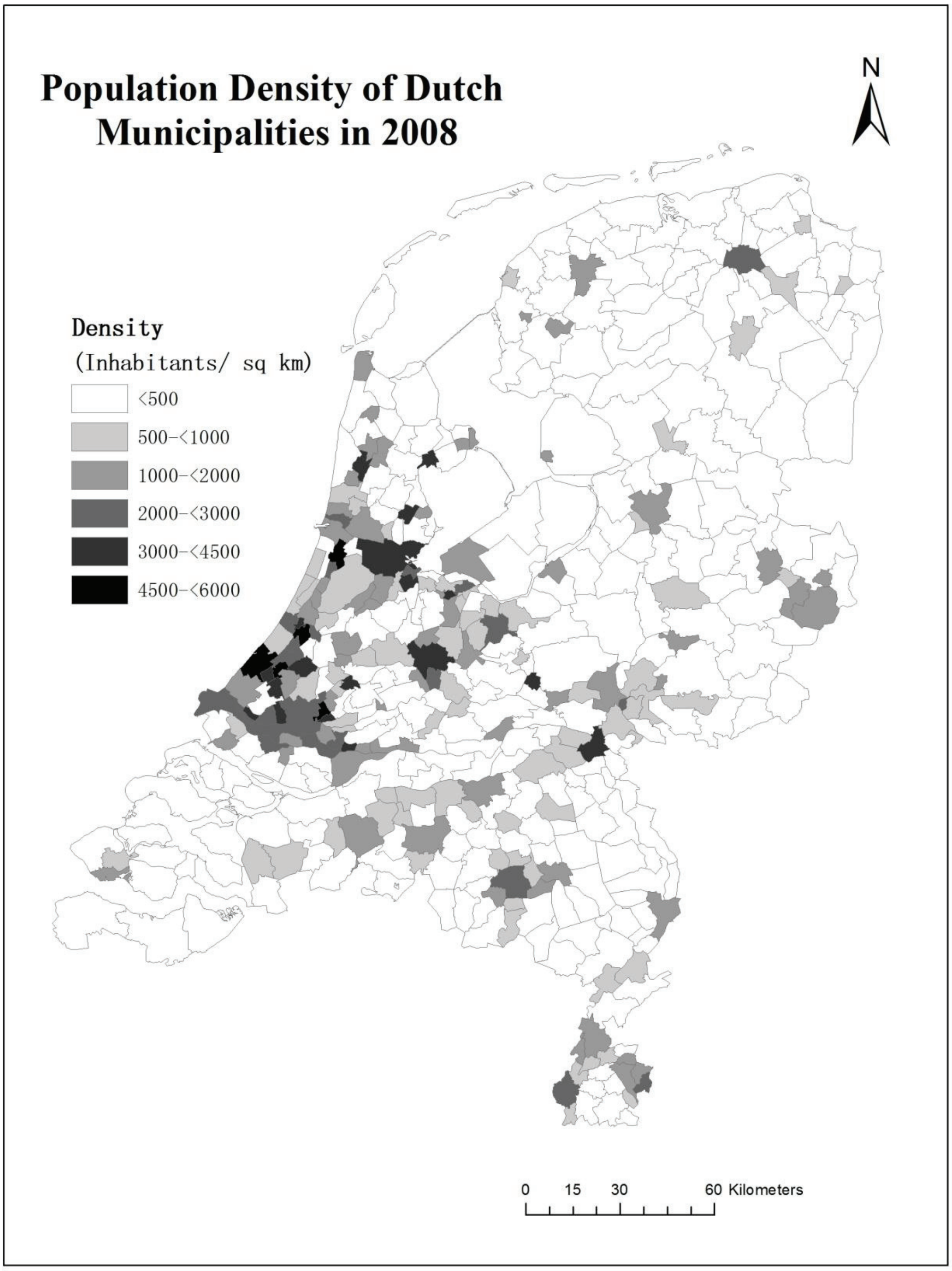


Figure 19 Population density

The average population density of the Netherlands is about 775 residents per square kilometre (land area without water body). However, the variation is very big among municipalities. A large concentration of population is found in the west of the Netherlands, mainly the sub-region of the Randstad. Den Haag has the largest population density (almost 6000), followed by its neighbouring municipality Leiden (5300). Municipalities in the east and north consist of smaller cities with also more rural area and are therefore much less populated and urbanized.

4.3.2. Density of Human Activities

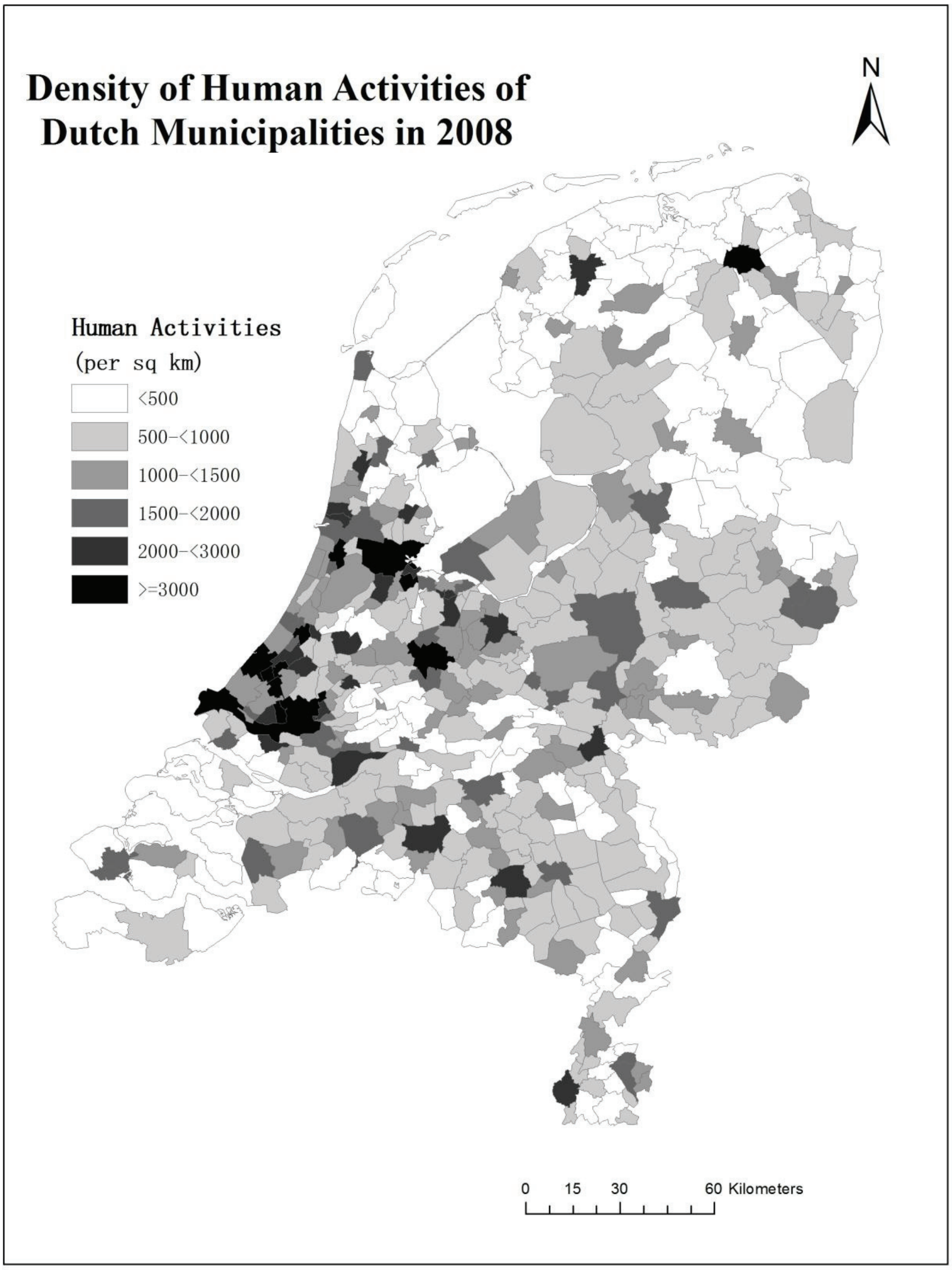


Figure 20 Density of human activities

The density of human activities is prepared by CBS in its annual report. It seeks the concentration of human activities for each address registered—how many human activities are within its one square kilometre area, including living, working, schooling, shopping, entertainment, and many other. The value for one municipality is the average of all its registered addresses.

4.3.3. Level of Urbanization

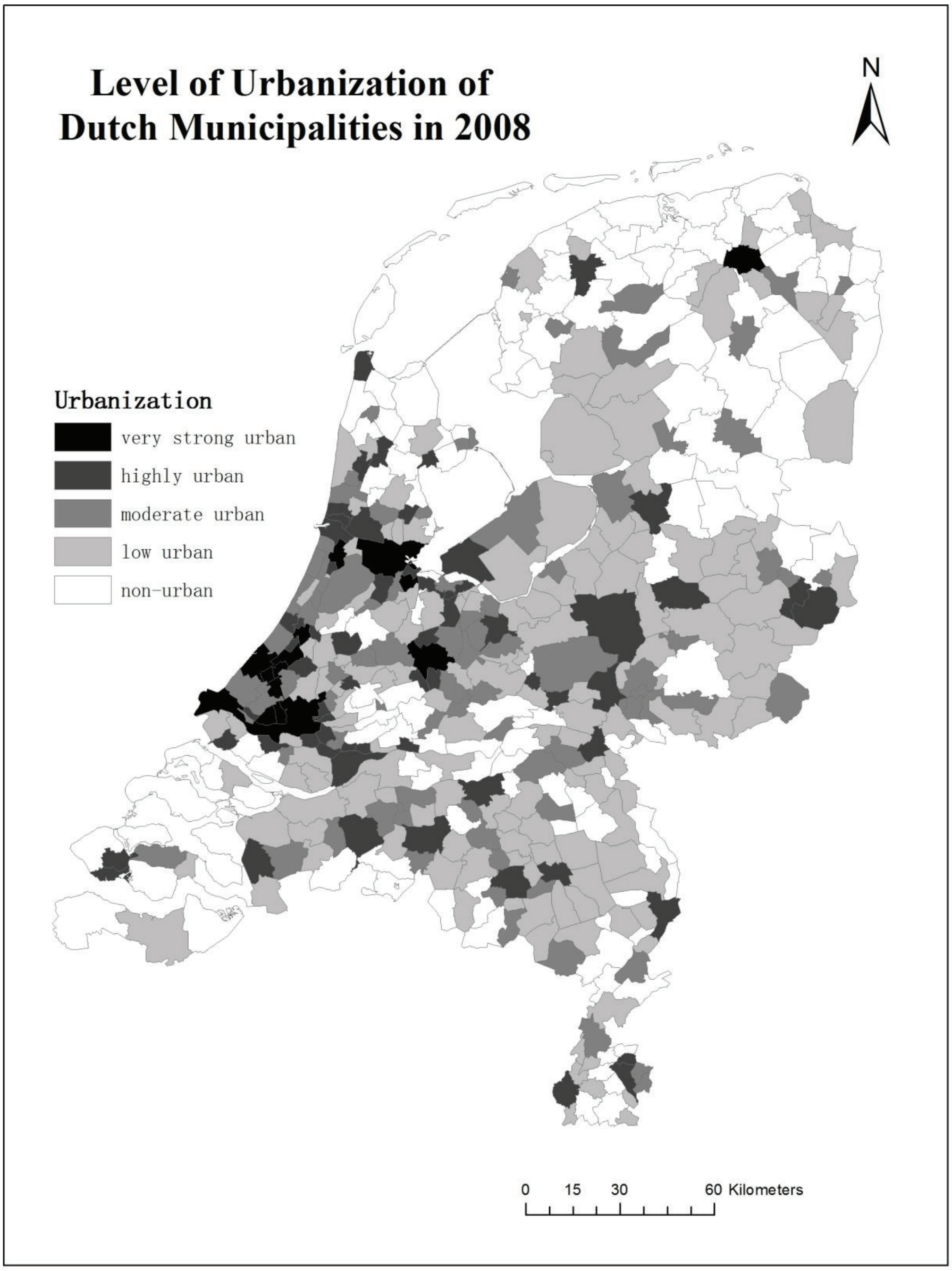


Figure 21 Level of urbanization

The level of urbanization is a categorical indicator. Since it is based on the number of addresses in one square kilometre, it looks very much like the distribution of population and human activity. According to CBS (2011), municipalities with more than 2500 addresses per square kilometre are classified as very strong urban, while municipalities with less than 500 addresses are classified as non-urban. See figure 21.

4.3.4. Equal Distance

More importantly, deeper exploration and understanding of the secondary data of CBS statistics help to create more useful urban form indicators and partially solve the problem of the absence of land use mix data. Originally, in order to calculate the degree of land use mix, for each municipality, the area of residential, commercial, and industrial should at least be available at a lower scale so that after spatial aggregation the land use mix for each municipality could be derived. However, such detailed information is not available for this research. Though using satellite image to produce land use mix information seems as a possible way, it is very time consuming and the accuracy is not ensured. However, although there is no information on different kinds of land use for each Dutch municipality, the nearest distances to different activities are available from CBS. The purpose of calculating the degree of land use mix starts from the perspective that the more mixed the urban land use, the shorter the distances between the trip origins and the destinations, which would create an influence on the mode choice of the trip maker, i.e. the shorter the distance, the more likely that they would use active transport (walking and cycling) and public transport. Since the nearest distances to activities (school, GP, hospital, restaurant, large supermarket, library, cinema, and sports centre) are available, it is possible to calculate the average distance to different services.[2] In this research, the weighted distance is calculated. A statistical analysis of the sample trips reveals the frequency of different trip purposes. This information creates the basis for the weighing of the distances:

The average distance to different activities (weighted) =

$$(a_1 * AF\_GP + a_2 * AF\_hospital + a_3 * AF\_primary\_school + a_4 * AF\_VMBO + a_5 * AF\_HAVO/VWO + a_6 * AF\_restaurant + a_7 * AF\_large\_supermaket + a_8 * AF\_library + a_9 * AF\_cinema + a_{10} * AF\_swimming\_pool) / 13$$

Where $a_{1,2} = 0.5$, $a_{3,4,5,6,8,9,10} = 1$, and $a_7 = 5$

AF: average distance to the nearest service destination.

Figure 22 Formula of Equal Distance

The alpha parameter for each activity is based on the frequency of trip purposes of MON 2008 sample trips (more than 130,000).

[2] Average distance to different services and provisions are calculated on paved roads at the level of neighborhood (CBS, 2011).

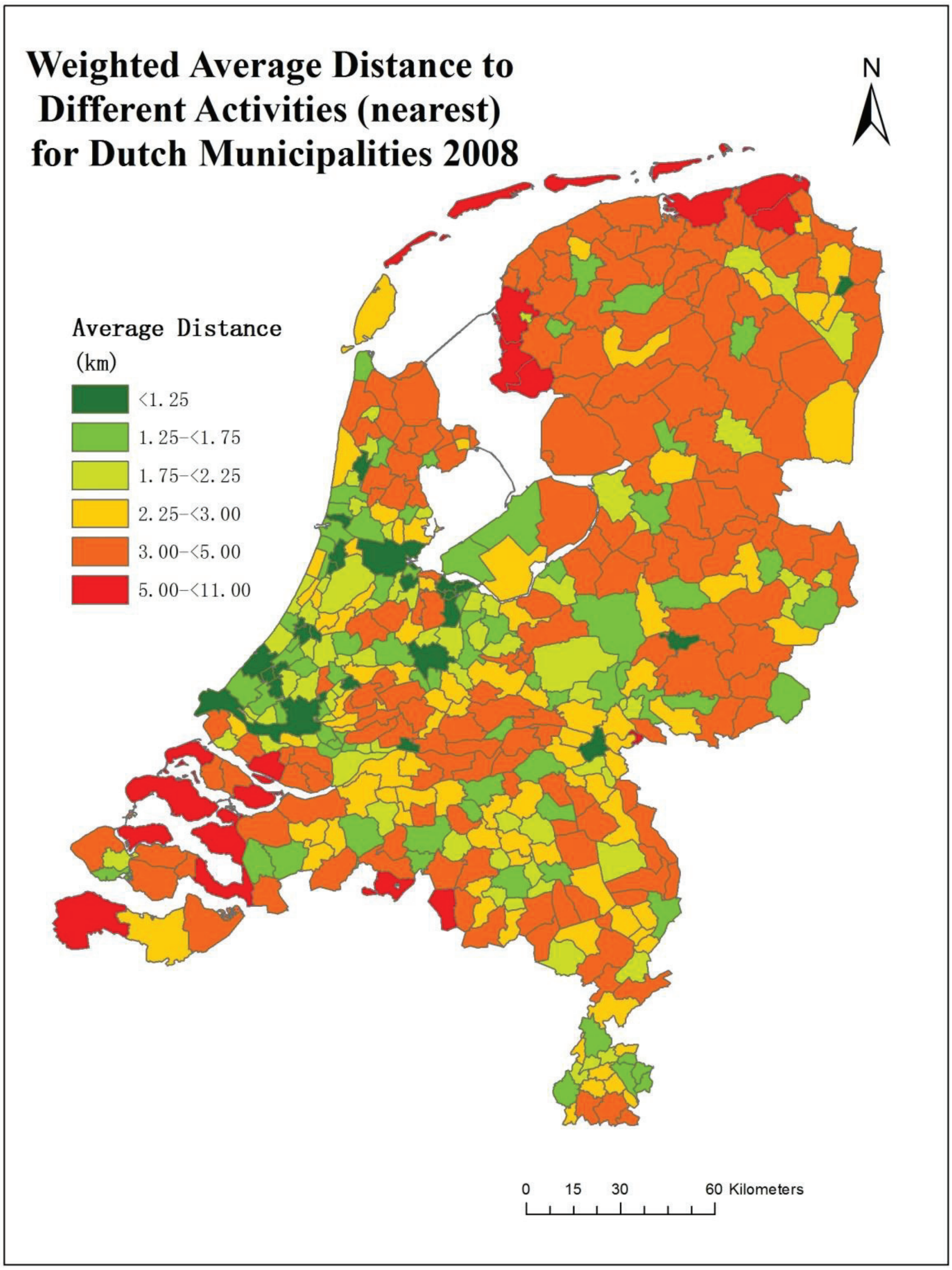


Figure 23 Equal distance

The average distance of cycling trips is 2.96 km (2008) and 2.99 (2004-2009 average). The majority of cycling trips are shorter than 2.5 km (61%), and less than 18% of cycling trips are longer than 5 km. As shown on the map, several cities on the western coast have very short distances to different activities and services while cities in the northern and south-western part have long distances to social activities and services. This map not only depicts the average distance to the nearest activities for different purposes, but also reflects the land use situation. A compact and mixed land use pattern would create shorter distance to the nearest activity of different purposes while a dispersed land use pattern would have the opposite effect. So on average, the shorter the distance, the more mixed land use of the municipality; the longer the distance, the more dispersed and scattered land use. As can be seen from the map, short distance can be found in Amsterdam (1 km), Den Haag (1 km), Leiden (0.94 km), Delft (0.92 km) and long distance is found in island municipalities, delta area municipalities and other peripheral municipalities (more than 5 km and up to 11 km).

4.3.5. Cycling Infrastructure Density

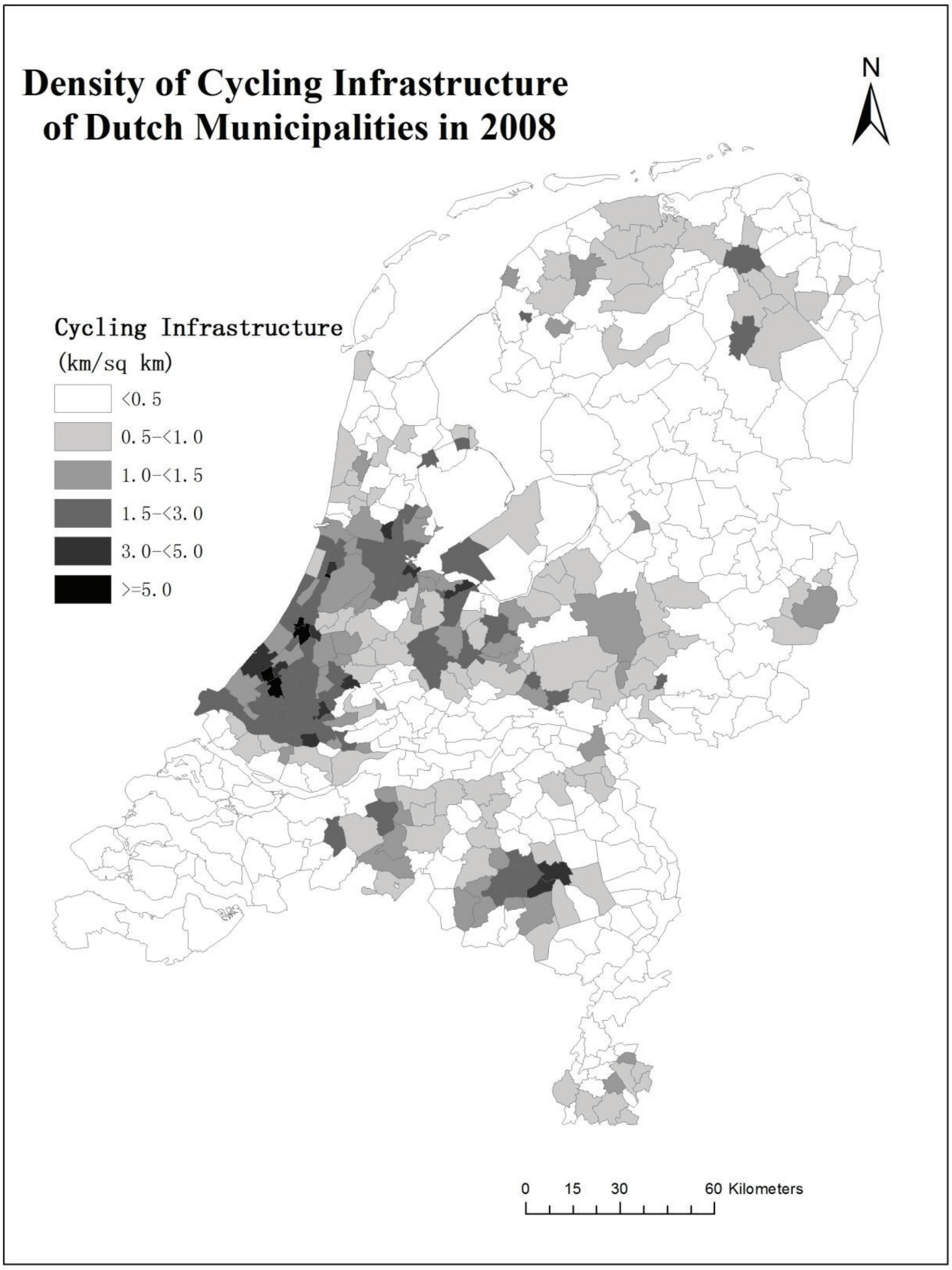


Figure 24 Cycling infrastructure density

Since the Dutch roads shapefile is available from CloudMade, for each municipality the total length of cycling path is calculated. For a deeper perspective, the density of cycling infrastructure is presented here. Cycling infrastructure density is the length (km) of cycling path on one square kilometre land. In principle, the less cycling path of an urban area, the more detour cyclists would encounter, and the less likely that they would frequent their destinations by bicycle.

However, the provision of cycling infrastructure is not the sole factor that influences the cycling level. The length and the density of cycling infrastructure only provide the basic accessibility of getting a bike on the road. They do not describe the infrastructure in a qualitative way. There are many different types of cycling infrastructure. Some cycling paths share the same road infrastructure with automobiles but are painted in colour, or separated by a line; some cycling paths have their own "track" (separated by a physical barrier) though cyclists and car drivers are still using the same roads; some other cycling paths are totally off-roads and the infrastructure is only designed for cyclists. Different types of cycling paths in the Europe are reviewed and pictured by Pucher et al., (2010). For example, in Copenhagen there are cycling paths which contradict the flow of cars, and in some other cities the cycling paths are designed in different positions to cars (sides and in the middle). According to the degree of separation from automobiles, Garrard et al.,(2008) categorizes three types of cycling facilities: (1) off-road path, (2) on-road lanes, and (3) no bicycle facility. Different cycling infrastructures have different ability to attract cyclists. For example, female cyclists show preferences for using off-road paths rather than on-road lanes and no bicycle facility in their research(Garrard, et al., 2008).

Besides cycling path types, their physical quality (pavement, width, clear signs, street lighting during night, etc.) can influence people's travel behaviour. However, such information, together with the different types of cycling paths, is not included in this research due to the lack of data and field survey.

4.4. Building the link between CVoC and urban form

To summarize, after the data preparation and processing, different sets of data are made readily available to test the relation between climate value of cycling and urban form.

For CVoC, four different indicators are calculated for each Dutch municipality. They are:

(1) Total CVoC: Total induced emission of CO_2 for one municipality of the given year

(2) Per Capita CVoC: Average induced emission of CO_2 per inhabitant of the given year

(3) Unit CVoC: Induced emission of CO_2 per cycling kilometre

(4) CVoC Density: Induced emission of CO_2 per square kilometre of the municipality

The revised hypotheses are:

Table 18 Revised Hypotheses

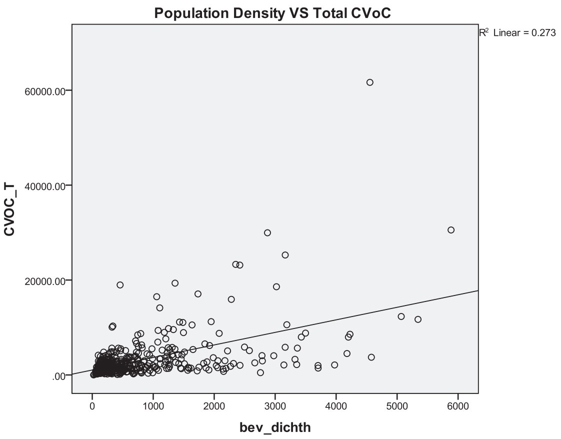
The higher the density (both population and activity); and the higher the urbanization level	the higher the total CVoC
	the higher the per capita CVoC
	the higher the CVoC density
	the lower the unit CVoC
The shorter the equal distance	the higher the total CVoC
	the higher the per capita CVoC
	the lower the unit CVoC
	the higher the CVoC density
The higher the cycling path density	the higher the total CVoC
	the higher the per capita CVoC
	the lower the unit CVoC
	the higher the CVoC density

4.5. Statistical analysis—testing the relation between CVoC and urban form

4.5.1. Density and CVoC

4.5.1.1. Population density

The Pearson Correlation between total CVoC and population density is .523 at the significance level of 0.01 (two-tailed). So the linear R square for the relation is 0.273. The assumption behind the hypothesis is that urban area with high population density could create more possible transport modes for residents, especially active transport mode (walking and cycling). The distance between trip origins and destinations would be shorter so that residents are encouraged and also willing to use bicycle. So in higher population density urban area, more trips will be realized using bicycle making the total climate value of cycling higher than urban area with lower population density. There is no significant correlation between population density and per capita CVoC. And there is no significant correlation between population density and unit CVoC. The Pearson correlation between population density and CVoC density is the highest among all the relations being tested, with a value of .940 at the significance level of 0.01(two-tailed). As is proved in the correlation between total CVoC and population density, these two variables are highly positively correlated. High population density urban area generates more cycling trips thus making the total CVoC and CVoC density high. Low population density urban area would have the opposite effect.



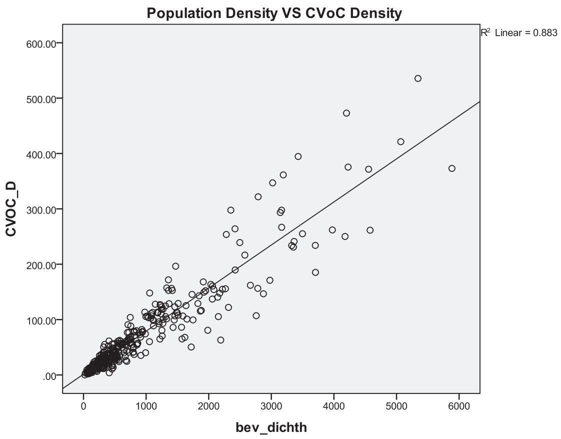
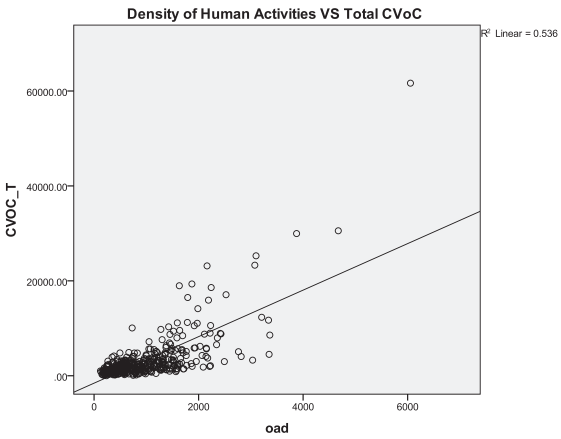


Figure 25 Scatter plot—Population density VS total CVoC (left)

Figure 26 Scatter plot—population density VS CVoC density (right)

4.5.1.2. Density of Human Activities

The Pearson correlation between human activity density and total CVoC is .732 at the significance level of 0.01(two-tailed). A fairly good fit line with R square of 0.536 is presented. Since the indicator describes how many activities on average are within 1 square kilometer of the registered address, it represents the number of activities that residents could reach within one square kilometer of his or her residence. Of course these activities are within cycling distance so that to reach these activities a large proportion of trips would be realized through the use of bicycle. The higher the activity density creates more potential destinations within cycling distance, thus generating more cycling trips and making the climate value higher. Similarly, there are no significant correlation between density of human activities and per capita CVoC and unit CVoC.



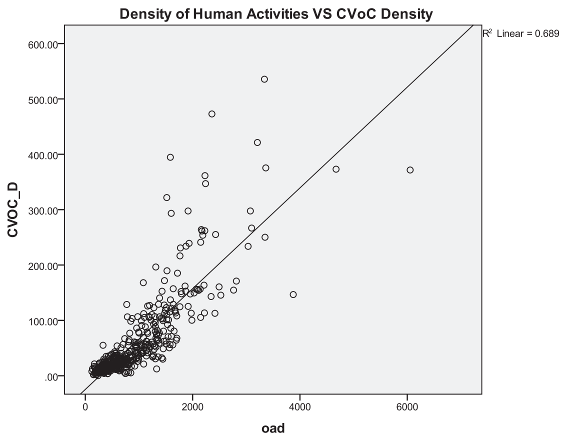


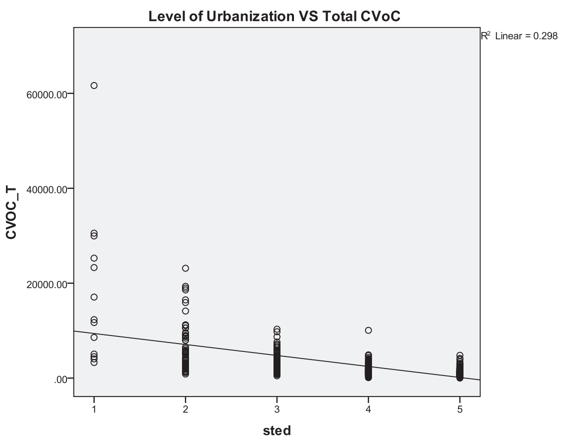
Figure 27 Scatter plot—Density of human activities VS total CVoC (left)
Figure 28 Scatter plot—Density of human activities VS CVoC density (right)

The Pearson correlation between activity density and CVoC density is .830 at the significance level of 0.01(two-tailed), and the linear R square for them is 0.689. Take one square kilometer of urban area as an example, the more human activities within this area, the needs of residents of their daily practice could be met within the area, making their trips short enough to use bicycle. So the climate value in this urban area would be higher.

4.5.1.3. Level of urbanization

Similarly, for the relation between the level of urbanization and CVoC, significant correlations are found for total CVoC and CVoC density, with a Pearson correlation of -.546 and -.765 respectively at the significance level of 0.01(two-tailed).

The level of urbanization is a categorical indicator. The higher the value, the less urbanized the area, and fewer addresses are registered in one square kilometre. A high level of urbanization yields more residential and commercial and other land use, and makes the population density and human activity density high. On the contrary, low level of urbanization suggests long distance between people and activity (trip destination), the longer the distance, the less likely that people would cycle to the destination, the lower value of CVoC.



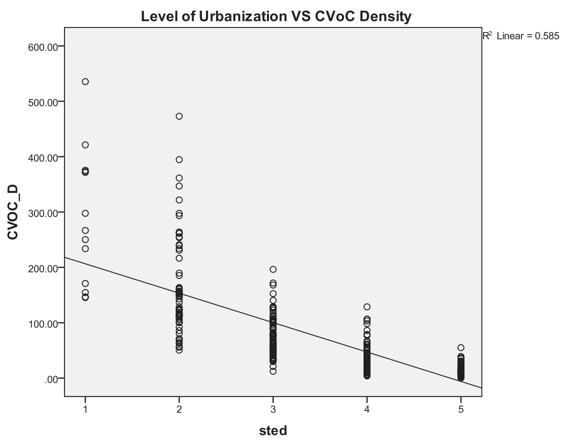
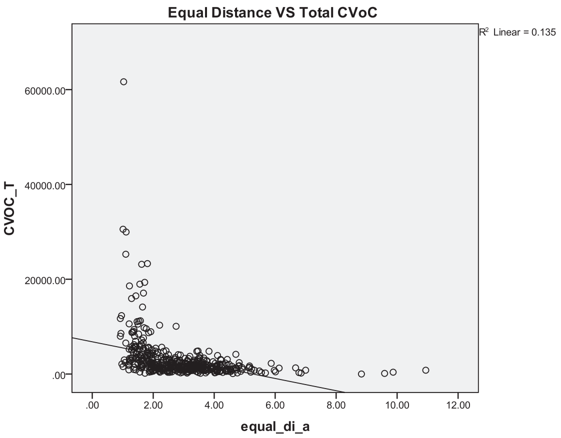


Figure 29 Scatter plot--- level of urbanization VS total CVoC (left)
Figure 30 Scatter plot—level of urbanization VS CVoC density (right)

4.5.2. Diversity and CVoC

The indicator of equal distance serves as a representation of land use diversity. The shorter the equal distance (for different activities), the more diverse the land use, more trips would be realized using bicycle; the longer the distance, the more scattered and dispersed the land use, cycling will no longer be a competitive transport mode. However, the effect of short distance decreases significantly when the distance is approaching 2 km, as seen from the scatter plot below. At least it could be concluded that municipalities with long equal distance do not have a high value of CVoC.



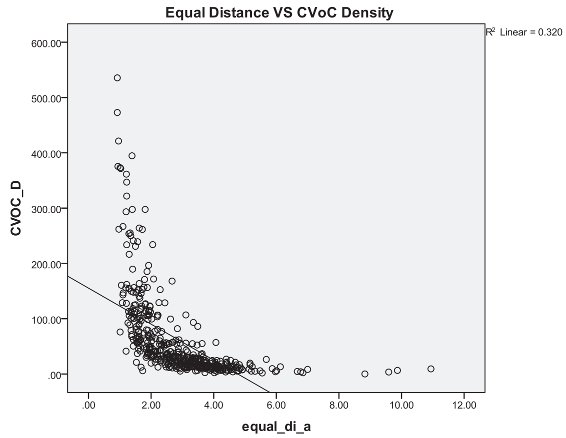


Figure 31 Scatter plot—equal distance VS total CVoC (left)
Figure 32 Scatter plot—equal distance VS CVoC density (right)

4.5.3. Design and CVoC

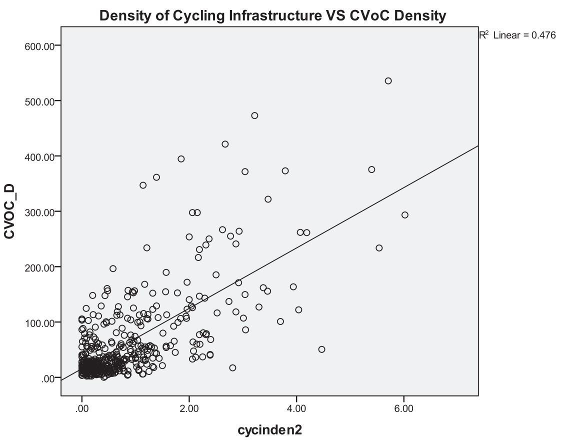


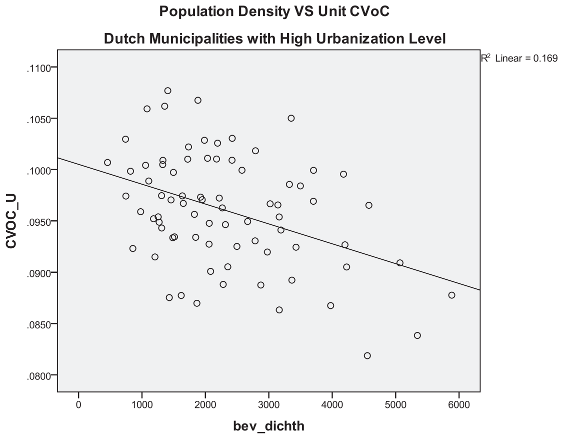
Figure 33 Scatter plot—cycling infrastructure VS CVoC density

The provision of cycling infrastructure serves as the basis of promoting the use of bicycle. The higher the value, the more complete the cycling path network. A good cycling network would encourage cycling, thus making the CVoC density high. However, the effect of encouraging cycling of infrastructure network does not pertain with the increase of network density. There might be a threshold, at which the network is comparatively good enough and no extra cycling trips would be generated by increasing the density of cycling infrastructure.

4.5.4. Test 4: Specific municipalities and their CVoC

Previously the statistical test for all Dutch municipalities did not show any correlation between Unit CVoC and urban form indicators. It is possible that some pattern or relation only exist in its sub-group. Here Dutch municipalities of high urbanization level and large population are selected out for further test.

For Dutch municipalities with urbanization level of 1 (very strong urban) and 2 (highly urban), it is found that their Unit CVoC are correlated with population density, the density of human activities, equal distance, and the density of cycling infrastructure. However, such correlations are comparatively weak.



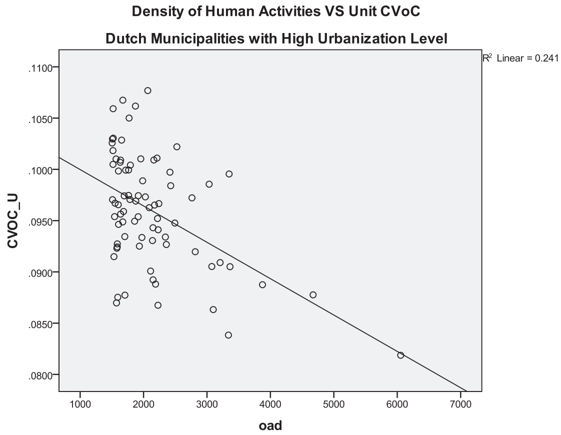
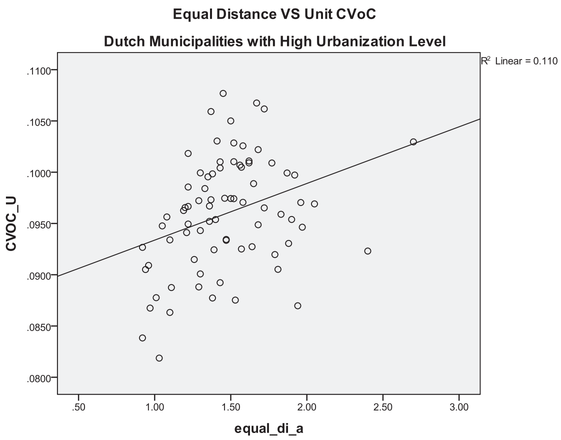


Figure 34 Scatter plot—population density VS unit CVoC (left)
Figure 35 Scatter plot—density of human activities VS unit CVoC (right)



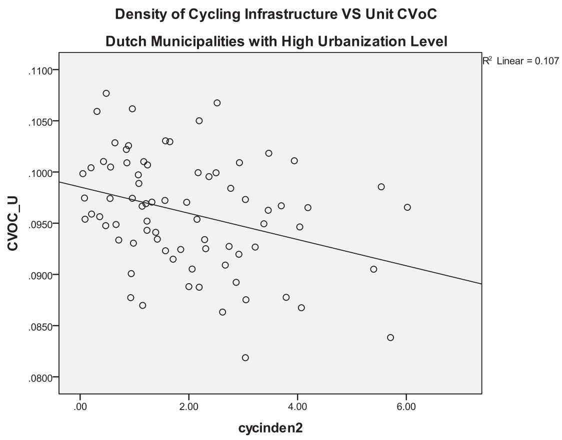
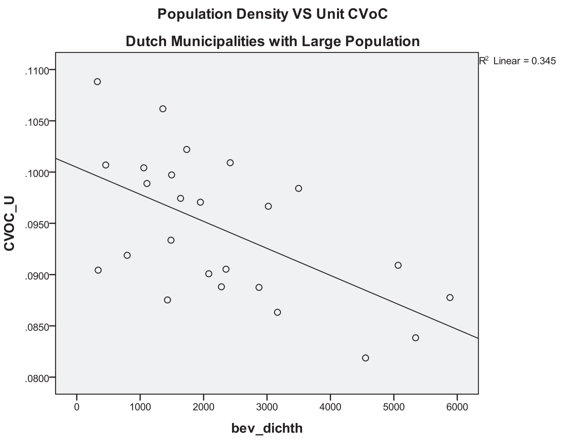


Figure 36 Scatter plot—equal distance VS unit CVoC (left)
Figure 37 Scatter plot—cycling infrastructure density VS unit CVoC (right)

For Dutch municipalities with population more than 100,000, the correlations between Unit CVoC and urban form indicators get stronger. It seems that for large Dutch municipalities, they behave like what have been predicted: the higher population density, higher density of human activities and shorter distances to different services discourage the use of automobiles and encourage active transport and public transport, which make the unit CVoC lower. With higher density of population and human activity, and shorter distance to destinations, cycling trips are more likely to be substituted by walking, bus and other public transport, rather than automobiles. For example, Amsterdam in this group has the lowest Unit CVoC. Walking and public transport substitute most of its cycling trips.



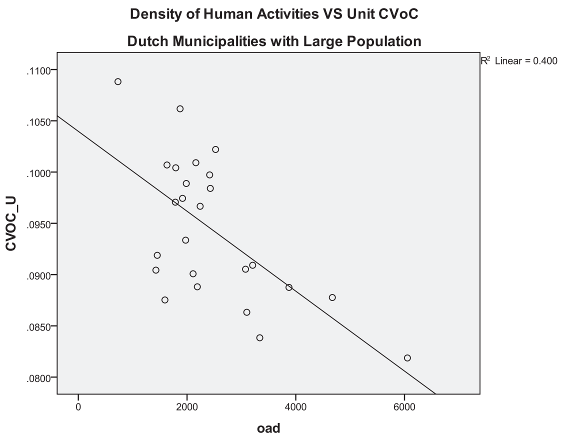
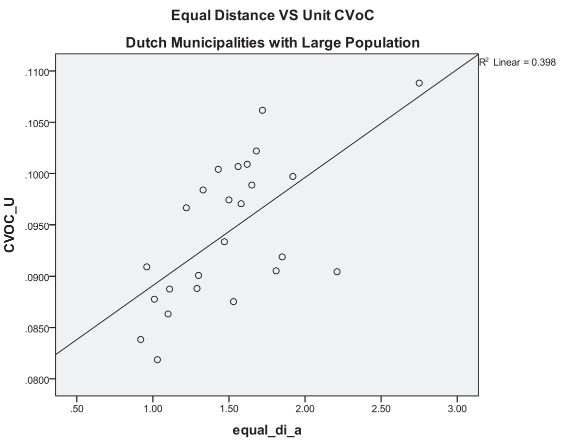


Figure 38 Scatter plot—Population density VS unit CVoC (left)
Figure 39 Scatter plot—Density of human activities VS unit CVoC (right)



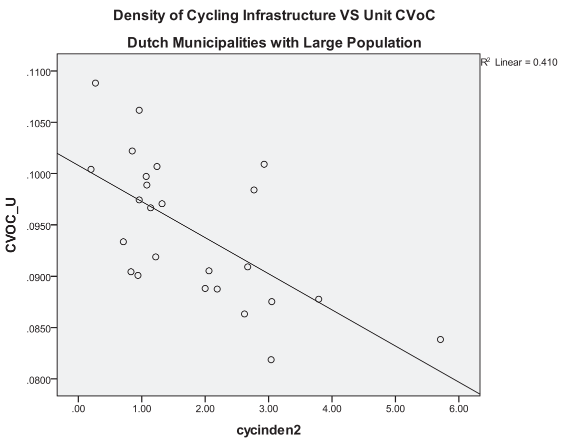


Figure 40 Scatter plot—equal distance VS unit CVoC (left)
Figure 41 Scatter plot—cycling infrastructure density VS unit CVoC (right)

4.5.5. Discussion on statistics

Previously it is hypothesized that there is a linear relation between urban form indicators and CVoC. However, from above performed statistical analyses it is found that the relation between per capita CVoC, Unit CVoC and urban density, diversity, and design is not actually linear.

Recognizing the trend of average cycling share in each urbanization level (also representing population density and human activity level) helps to understand the failure of proving the hypothesized linear relation. As shown below (see figure 42), the cycling share is low in least urbanized (label 5) municipalities where cyclists find fewer opportunities to make short distance trips. Then cycling share starts to climb to the maximum in municipalities with medium level of urbanization (3). Afterwards, cycling share starts to decrease in highly urbanized (2) and very strong urban (1) municipalities since in these municipalities good public transport services are competing for travellers. Such trend—cycling share increases with the level of urbanization, but then decreases when the urban environment is getting too strong— has also been found in a previous research (Rietveld & Daniel, 2004).

Since cycling share is highly correlated with per capita CVoC, which has been discussed in section 4.2.2 (see figure 16), the trend for per capita CVoC in each level of urbanization should be the similar. Because in less urbanized and populated municipalities, distances between destinations are longer so that cycling share is comparatively lower. With the increase of urbanization level, cyclists find distances short enough to cycle and create more per capita CVoC. Suddenly, when municipalities are urbanized and populated enough with good provision of public transport, cycling share goes down because of the competition from public transport and the average per capita CVoC decreases (see figure 43).

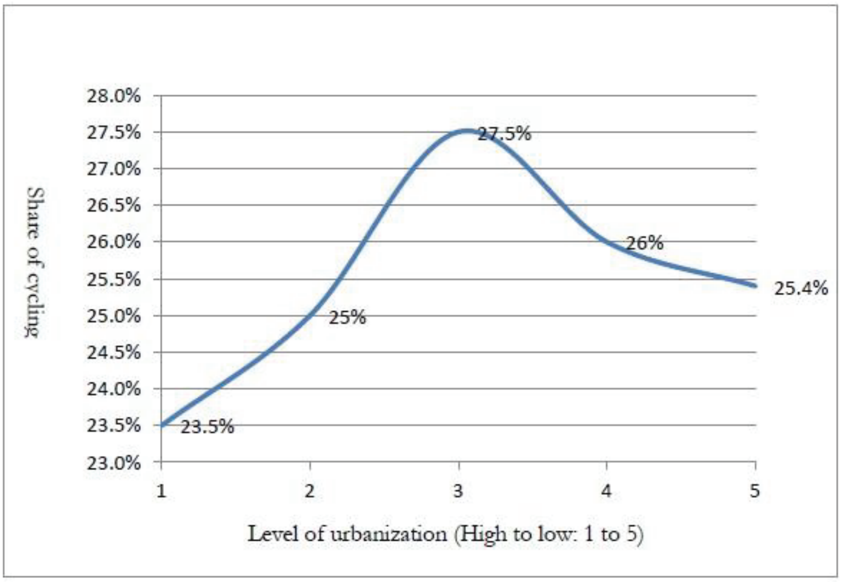


Figure 42 Average share of cycling in each level of urbanization

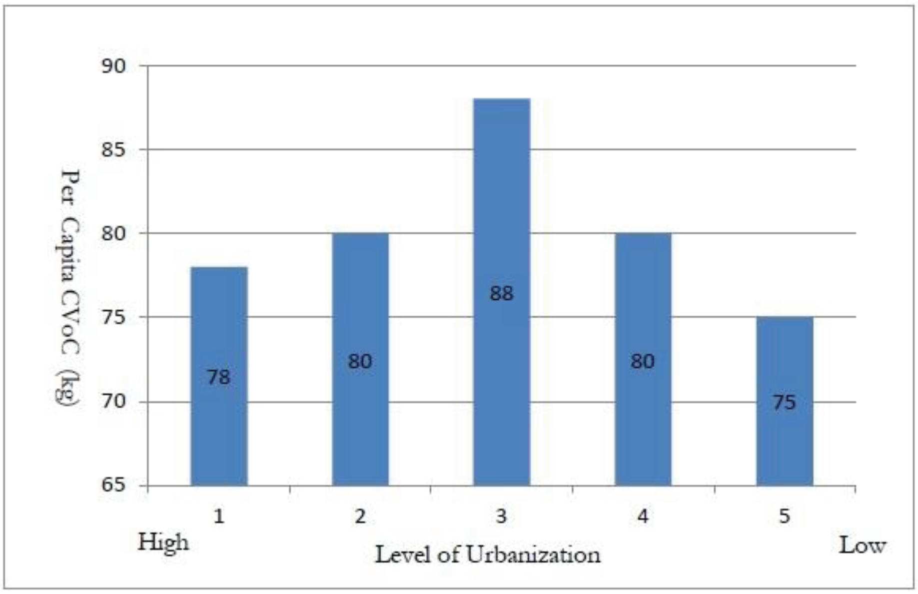


Figure 43 Average per capita CVoC in each level of urbanization

The average share of cycling and average per capita CVoC in each level of urbanization are proved to be significantly different from the average value of other levels. It seems that the level of urbanization could serve as a good urban form indicator since it explains a lot of issues. For example, the Equal Distance in municipalities with high to low level of urbanization increases, as shown in the table below, with ED very short in highly urbanized municipalities and very long in rural municipalities. Such difference in each level is also statistically significant (see table 19). So where would people mostly frequent their destinations by cycling? Is it in highly urbanized municipalities? Or in municipalities with a medium value of ED? The ED is so short in municipalities with very strong urban environment, in which walking and public transport would be competitors against cycling. Probably modal share of cycling would be higher in municipalities with medium level of urbanization, which does not make their ED short enough to walk, nor too long to cycle.

Table 19 Average ED, cycling infrastructure density, and unit CVoC in each level of urbanization

Level of Urbanization	Average equal distance (km)	Cycling infrastructure density (km/km²)	Unit CVoC (kg)	Number of cases
1	1.25	3.13	0.92	13
2	1.52	1.75	0.97	64
3	2.01	0.98	0.98	82
4	2.91	0.63	1.00	154
5	4.24	0.33	0.98	128
Total	2.88	0.84	0.98	441

Finally, the relations between CVoC and urban form become clear: more urbanized municipalities have higher population density, higher density of human activities, shorter equal distance, more provision of cycling infrastructure, and also good public transport system. With the provision of public transport and the short equal distance making destinations within walking distance, cycling in more urbanized municipalities are facing the competition from bus, tram, metro, and walking. The competition effect from public transport and walking makes Unit CVoC lower in more urbanized municipalities. For cycling share, it increases from rural municipalities to more urbanized municipalities, and then decreases because the urban environment becomes so strong that distances are short enough to walk or public transport is also appealing to trip makers. So municipalities with medium level of urbanization would have the highest share of cycling and per capita CVoC. Municipalities with very strong urban environment would have the lowest Unit CVoC—suggesting their substitution modes are less emitting. Total CVoC and CVoC density would be much higher in populated municipalities than rural municipalities.

To conclude, municipalities with medium level of urbanization (namely level 3, with 1000 to 1500 addresses in one square kilometre land) have the best cycling performance in The Netherlands. The distances between destinations are suitable for cycling. In municipalities with more urbanized environment, population, and activity, average distance between different activities becomes shorter so that people can frequent their destinations by walking. Most of them also have good performance of public transport, making it an attractive mode. Cycling performance would be poorer in less urbanized and rural municipalities, where distances are too long to cycle and the provision of cycling infrastructure is also very little. Future urban development would consider the fact that urban environment with less than 1000 address per square kilometre would fail to encourage cycling and will make transport alternatives also less sustainable. Recognizing the increasing problems of urban sprawl and automobile use caused by land conversion to urban uses in other European cities (Kasanko et al., 2006), Dutch planners should incorporate strategies to reduce GHG emissions from the transport sector through urban plans which increase the use of public transport and non-motorized travel (cycling and walking)(Blanco, et al., 2011).

4.6. Summary—revisiting research questions

So far, the CVoC for Dutch municipalities have been successfully modelled with four indicators. Their associative relations with cycling share and urban form indicators have been tested. The overall goal to assessing the Climate Value of Cycling under different urban forms of Dutch cities is accomplished. Here the research questions are revisited to see if each of them has been answered.

4.6.1. Informational research questions

Some research questions are informational, such as '1.5 What are the emission factors for each mode?' and '2.1 What urban form dimensions and their indicators are possibly related to modal split?' The first question is answered by the provision of Dutch emission factors in section 3.2.2.2 (see table 8) and by comparing with ADB emission factors it can be concluded that the ridership of Dutch public transport should be increased to make public transport more sustainable. The second question is answered in literature review (section 2.5) in which three dimensions (3D) and their sub-level indicators are discussed. Later in this research limited by data availability, indicators such as population density, density of human activities, level of urbanization (under dimension 'density'), equal distance (under dimension 'diversity') and cycling infrastructure density (under dimension 'design') are chosen as primary indicators for analysis (section 4.3).

4.6.2. Methodological research questions

Some research questions are methodological, such as '1.3 How to classify all the trips?' '1.4 How to substitute the cycling trips by other modes?' and '2.2 How to quantify each urban form indicator?' The first two questions are answered in model description (section 3.2.2.1). The quantification of urban form indicators are supported by secondary data (section 3.2.3). Some indicators are directly used, such as population density, density of human activities, and level of urbanization. Others are created by the author's elaboration, such as the equal distance and cycling infrastructure density.

4.6.3. Other research questions

The rest of the research questions are the results and implications of the CVoC modelling and the statistical analysis between CVoC and urban form. They are:
'1.1 What is the modal split of cycling for each municipality?'
'1.2 What is the total distance travelled using cycling?'
'1.6 What is the Climate Value of Cycling for each Dutch municipality?'
'3.1 What is the relation between CVoC and urban form?'
'3.2 Whether thresholds exit and if so what are the thresholds for each indicator?'
'4.1 What suggestions can be made to encourage sustainable urban transport?'
'4.2 What are the policy/planning implications of the result?'
In a nutshell, the overall cycling share in The Netherlands is 26% and intuitive cut-off values of 15% and 25% are used to indicate different level of cycling performance. Every day, 12.9 million cycling trips are realized in The Netherlands with an average cycling distance of 2.99 kilometres. Cycling trips together create an annual CVoC of 1.36 million tons of CO_2. On average each Dutch citizen creates a CVoC of 82 kg CO_2. Each kilometre of cycling equals 98 grams of CO_2. The relations between total CVoC, per capita CVoC, Unit CVoC and urban form indicators are discussed in section 4.5. Suggestions to encourage sustainable urban transport are given to different types of Dutch municipalities based on their per capita CVoC, cycling share, and Unit CVoC in section 4.2.2 and section4.2.3. For future urban land use development, it is suggested that no urban development should be planned with a density less than 1000 addresses per square kilometre. Since under this level of urbanization, cycling share goes down, and the share of private cars goes up. Nevertheless, it is not easy to provide public transport in less urbanized environment, neither it is easy to provide cycling infrastructure. In general, high density urban development is encouraged to make destinations so close that cycling would be appealing to people. In very urbanized environment, many trips can be internalized so traffic can be reduced. People also find a variety of transport modes, many of them are less emitting than private cars. However in an urban environment where distances between activities become too long, private car seems to be the only option to facilitate the mobility. At the same time, transport policies and projects should further be implemented to encourage low carbon urban transport, such as parking regulations, provision of cycling facilities and parking, lowering the tariff of public transport, etc.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

5.1.1. Cycling in the Netherlands

Cycling is part of the Dutch culture. People use bicycle as an active transport means regardless of their gender, age (as soon as physically active for cycling), income, purpose, and travel time of the day. Some people even cycle in rainy and snowy days and they just simply get used to cycling. Cyclists are aware that cycling is good for their health and the environment. On average, Dutch Municipalities have a cycling share of 26%. More than a quarter of Dutch municipalities have a share of cycling of 30% and above. Cycling rate decreases significantly with the increase of trip distance. 61% of all cycling trips are shorter than 2.5 km. On average, 12.9 million trips are realized by cycling in the Netherlands in a single day. These trips together equal a total distance of 38.7 million km.

5.1.2. Climate Value of Cycling for the Netherlands

In this research, the Climate Value of Cycling model has been revised by using multiple years' observations for a better assessment. The MON data 2004-2009 have been stacked to render a better representation of Dutch population and their trips rather than using a single year data. Estimated by the model in this research, Dutch cities create a total annual Climate Value of Cycling of 1.36 million tons of CO_2 on average from 2004 to 2009. Such amount of CO_2 needs 54.4 million trees to absorb in a single year. It also equals 54.4 million EUR according to the penalty level 1 standard of the European Union's Emission Trading System. Each Dutch citizen contributes 82 kg of CVoC in a year on average. High per capita CVoC is found in municipalities with high cycling rate. The average Unit CVoC for all Dutch municipalities is about 0.098 kg. This is between the emission factor for metro/tram (0.087 kg/km) and train (0.102 kg/km). High Unit CVoC municipalities are running higher risk of inducing more CO_2 than other municipalities if their cycling share is not maintained.

5.1.3. Urban forms of Dutch municipalities

The Netherlands as a whole is highly populated compared with other European countries. Some Dutch municipalities are very much populated and urbanized, with a population density 4 to 7 times compared to the national average. However, more than half of Dutch municipalities have a population density less than 500 inhabitants per square kilometre. They are much less urbanized and the density of human activities in such municipalities is also very low. With an average equal distance of 2.88 km, Dutch people could find their destinations for different purposes within cycling distance, compared to the national average distance of cycling trips, which is 2.96 km. Some municipalities have an equal distance around 1 km, which is almost friendly for walking. So land use in the Netherlands is not only compact but also diverse. People can find different activities within short distances. Cycling infrastructure is well provided in populated municipalities. However, it is not a determinant of the cycling level for Dutch municipalities.

5.1.4. Relations between CVoC and urban form in the Netherlands

The CVoC (total and density) for Dutch municipalities are positively correlated with population density, density of human activities and urbanization level. Municipalities with large CVoC are populated, highly urbanized, and well provided with cycling infrastructure. Their equal distance is also short, suggesting a compact and diverse land use pattern. The per capita CVoC is highly correlated with modal share of cycling, which however is not in a linear relation with urban form indicators. Cycling share and per capita CVoC tend to be lower in least urbanized municipalities in which long distances create barrier for cyclists; then they increase in more urbanized municipalities to their maximum; in municipalities with very strong urban environment, public transport becomes a strong competitor, making cycling share and per capita CVoC lower again. For municipalities with large population, their unit CVoC is negatively correlated with population density, density of human activities, and density of cycling infrastructure, and positively correlated with Equal Distance. It confirms with the hypothesis that high population/human activity /cycling infrastructure density, high urbanization level, and short Equal Distance discourage the use of private cars but encourage public transport and active transport (walking and cycling).

5.1.5. Policy responses to the results

Climate Value of Cycling, on the one hand, is the quantification that appreciates the cycling performance of each Dutch municipality; on the other hand, it also shows the risk of each municipality by looking at their differences in terms of per capita CVoC, Unit CVoC and cycling share in modal split. More cycling should be encouraged in municipalities with low cycling level (the bottom 1/4 line is 22.4%), especially those with combination of high Unit and per capita CVoC. There is room for municipalities with medium cycling level (22.4% to 30% as middle half) to increase their cycling share further. Those with high per capita and unit CVoC would receive more value when their cycling share is increased. For municipalities with very good cycling performance (1/4 above 30%), it is very important to at least maintain their current level, because their per capita CVoC are also high. Cycling would be regarded as more sustainable in high Unit CVoC municipalities because each cycling kilometre equals more emissions. However, the competing modes—the rest of the transport system is less sustainable because if cycling trips are decreasing, more emissions will be induced since they are more likely to be substituted by high emitting modes.

Since urban form depends on the planning and economic goals municipalities choose to implement in the long term, it is suggested that urban planning in the Netherlands continue to follow a dense and compact land use pattern in which travel demand can be reduced, distances between activities can be shortened, motorized transport can be discouraged, and cycling and walking would be more appealing. Experience shows that the Dutch policies work to avoid urban sprawl during the last three decades of last century (Mehrotra, et al., 2011). Such policies should be enhanced to make Dutch urban system more sustainable—both in terms of land use and transport. Though overall speaking cycling performance in The Netherlands is good, it only takes 7.3% of the total PKT. On the contrary, 76% of PKT of Dutch transport is done by private car (with car driver 50.2% and passenger 25.8%). Cycling should be further encouraged.

Nevertheless, for the transport system part, policies should be implemented to increase the ridership of public transport and the occupancy of private cars. According to the CE-Delft report (den Boer, et al., 2008), the ridership for Dutch public transport on average is 1 out of 3 seats (33.3%). However, many developing countries have a ridership of 80% to even 100%. The average occupancy of private car is 1.5. If a car on road is occupied by two people (driver and a passenger) or more, it would have the same emission level as the public transport. Increasing the occupancy for both could improve the sustainability of the motorized vehicles, thus decreasing the carbon footprint of the transport sector.

5.2. Recommendations

Climate Value of Cycling, compared with other concepts, quantification, or evaluation of cycling, is quite new to the scientific field. This research has focused on the modelling part to make CVoC for each Dutch municipality as accurate as possible. However, it does not solve the problem of discourage of trips and the redistribution of destinations when another transport alternative is available. Though it has been argued that the trip discourage effect would be small in The Netherlands, it is better to carry out a survey on this issue. For the redistribution of trip destinations, which would mostly happen for shopping trips, further investigation is needed. Another limitation of the model comes from the characteristics of the trips being considered. Since some 400 municipalities need to be modelled for their CVoC, the socio-economic background of the trip maker and trip purpose are left out from the original model (Massink, et al., 2011). In this research it is also assumed the utility values of other modes are not affected by the presence or absence of cycling, which actually should be tested for the IIA using the Hausman and/or the Small-Hsiao test (Hausman, 1978; Small & Hsiao, 1985). Future application of the CVoC model (Massink, et al., 2011) should include the two parameters and also test whether the IIA is violated or not. Total, per capita, and unit CVoC are explored in combination with cycling share. Other interpretation of CVoC and combination with other information such as vehicle ownership is encouraged.

Since this research is highly relied on the MON database, which is yearly available, it is promising to investigate the temporal change of the Dutch transport system, especially the cycling part. Thus it would be possible to have a better insight on the risk management when the trend is presented. It is also possible to evaluate the projects and policies that have been implemented in specific municipalities in encouraging cycling and discouraging private cars.

Policy responses based on CVoC for different types of municipalities are given. Primitive results of the relation between cycling and urban form are also presented. Future research can be taken from the perspective of how to further encourage cycling in The Netherlands through urban planning and urban transport policies.

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