Understanding the Impacts of Weather and Climate Change on Travel Behaviour

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Doctoral Thesis

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Abstract

Human behaviour produces massive greenhouse gas emissions, which trigger climate change and more unpredictable weather conditions. The fluctuation of daily weather corresponds to variations of everyday travel behaviour. This influence, although is less noticeable, can have a strong impact on the transport system. Specifically, the climate in Sweden is becoming warmer in the recent 10 years. However, it is largely unknown to what extent the change of travel behaviour would respond to the changing weather. Understanding these issues would help analysts and policy makers incorporate local weather and climate within our policy design and infrastructure management.

The thesis contains eight papers exploring the weather and climate impacts on individual travel behaviour, each addressing a subset of this topic. Paper I explores the weather impact on individual's mode choice decisions. In paper II and III, individual's daily activity time, number of trips/trip chains, travel time and mode shares are jointly modelled. The results highlight the importance of modelling activity-travel variables for different trip purposes respectively. Paper IV develops a namely nested multivariate Tobit model to model activity time allocation trade-offs. In paper V, the roles of weather on trip chaining complexity is explored. A thermal index is introduced to better approximate the effects of the thermal environment. In paper VI, the role of subjective weather perception is investigated. Results confirm that individuals with different socio-demographics would have different subjective weather perception even given similar weather conditions. Paper VII derives the marginal effects of weather variables on transport CO_2 emissions. The findings show more CO_2 emissions due to the warmer climate in the future. Paper VIII summaries the existing findings in relations between weather variability and travel behaviour, and critically assesses the methodological issues in previous studies.

SAMMANFATTNING

Mänsklig aktivitet producerar stora utsläpp av växthusgaser, vilket medför klimatpåverkan och mer oförutsägbara väderförhållanden. Under det senaste årtiondet har extrema väderförhållanden som kraftiga snöfall och översvämningar, lett till kaos och katastrofer i olika städer runt om i världen, vilket kostat miljardtals euro. Å andra sidan påverkar den dagliga variationen av väderleksförhållandena också individers dagliga resvanor. Denna påverkan, även om den är mindre påfallande, kan ha stor effekt på transportsystemet. Därför har det blivit viktigt att kunna förstå och förutsäga de möjliga individuella beteendeförändringarna med tanke på att klimatet och väderleksförhållandena kommer bli mer oförutsägbara och skadliga.

Exempelvis har det svenska klimatet blivit varmare de senaste tio åren. Väder och klimatmönster i södra och norra Sverige skiljer sig även signifikant ifrån varandra. Det är dock ovisst i vilken grad förändrande väderförhållanden orsakar förändringar av resvanor. Att förstå dessa mekanismer skulle hjälpa analytiker och politiker med att integrera lokala väder- och klimatförhållandens unika karaktär i utformningen av policy och infrastrukturförvaltning.

Doktorsavhandlingen innehåller åtta artiklar som utforskar påverkan av väder och klimat på individuella resvanor, var och en av dem utifrån olika perspektiv på detta ämne. Den första artikeln utforskar påverkan av väderförhållanden på en individs färdmedelval, med fokus på regionala skillnader. I den andra artikeln har individernas dagliga aktivitetstid, antalet resor/kedjor av resor, restid och färdmedelval modellerats samtidigt med en strukturekvationsmodell (SEM). Modellsystemet möjliggör för analytikerna att särskilja direkta och indirekta effekter av varje vädervariabel. I tredje artikeln fokuserade analysen på fritidsresenärer för att den andra artikeln visade att icke-pendlare är mer påverkade av väderförhållanden. Ett simultant modellsystem har utvecklats för att modellera aktivitets- och resmönster för icke-pendlare (ärenden såsom inköp eller fritid). Resultaten visar att det är viktigt att modellera aktivitets- och resevariabler för olika ärenden. Fjärde artikeln utvecklar en 'nested multivariate Tobit'-modell för att modellera avvägningar med hänsyn till tidsfördelningen för olika aktiviteter en given dag. Jämfört med andra möjliga modellalternativ kan denna modell beakta restid och färdmedelfördelningen som sekventiella och slumpmässiga komponenter som påverkar tidsfördelningen mellan olika aktiviteter. Resultaten visar att denna modell har en bättre prognosförmåga än traditionella modeller. I femte artikeln utforskas samspelet mellan väder och reskedjornas komplexitet. Ett termiskt index har introducerats för att göra effekterna av den termiska omgivningen mer exakta medan den rumsliga heterogeniteten av effekten av detta termiska index har utforskats med en rumslig expansionsmetod. Resultaten visar att den rumsliga fördelningen av effekten av termiskt index inte är likformig och att trenden skiljer sig åt beroende på det viktigaste ärendet i reskedjan. I sjätte artikeln har rollen av uppfattningen av väderförhållandena utforskats. Resultaten visar att individer med olika sociodemografiska egenskaper har olika uppfattningar av väderförhållandena, även under likadana väderförhållanden. Sjunde artikeln härleder marginaleffekterna av vädervariabler på transportrelaterade CO_2 utsläpp. Vädereffekterna på både individuella resvanor och fordonsutsläppsfaktorer har tagits i beaktning. Resultaten påvisar ökade CO_2 utsläpp på grund av det varmare klimatet i framtiden. Åttonde artikeln sammanfattar de befintliga resultaten avseende förbindelsen mellan vädervariation och resvanor och gör en kritisk bedömning av de metodologiska frågeställningarna i tidigare studier. Olika riktningar för framtida forskning har identifierats och föreslagits för att överbrygga klyftan mellan empiriska bevis och nuvarande praxis i samhällsekonomiska kalkyler.

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LIST OF PAPERS

I. Liu, C., Susilo, Y. O, Karlström, A. (2015). The influence of weather characteristics variability on individual's travel mode choice in different seasons and regions in Sweden. *Transport Policy*, 41: 147-158. doi:10.1016/j.tranpol.2015.01.001

II. Liu, C., Susilo, Y. O, Karlström, A. (2015). Investigating the impacts of weather variability on individual's daily activity–travel patterns: A comparison between commuters and non-commuters in Sweden. *Transportation Research Part A*, 82: 47-64. doi:10.1016/j.tra.2015.09.005

III. Liu, C., Susilo, Y. O., Karlström, A. (2014). Examining the impact of weather variability on non-commuters' daily activity–travel patterns in different regions of Sweden. *Journal of Transport Geography*, 39: 36-48. doi:10.1016/j.jtrangeo.2014.06.019

IV. Liu, C., Susilo, Y. O., Karlström, A. (2015). Jointly modelling individual's daily activity-travel time use and mode share by a nested multivariate Tobit model system. *Transportation Research Procedia: Papers selected for Poster Sessions at the 21st International Symposium on Transportation and Traffic Theory*, 9: 71-89. doi:10.1016/j.trpro.2015.07.005. Submitted to *Transportmetrica A.*

V. Liu, C., Susilo, Y. O., Karlström, A. (2015). Measuring the impacts of weather variability on home-based trip chaining behaviour: a focus on spatial heterogeneity. *Transportation*, 1-25. doi:10.1007/s11116-015-9623-0

VI. Liu, C., Susilo, Y. O., Termida, N. A. (2016). Subjective perception towards uncertainty on weather conditions and its impact on out-of-home leisure activity participation decisions. Paper presented at 6th International Symposium on Transportation Network Reliability, Nara, Japan. Submitted to *Transportmetrica B.*

VII. Liu, C., Susilo, Y. O., Karlström, A. (2016). Estimating changes in transport CO_2 emissions due to changes in weather and climate in Sweden. Presented at *95th Annual Meeting of the Transport Research Board*, Submitted to *Transportation Research Part D*.

VIII. Liu, C., Susilo, Y. O., Karlström, A. (2016). Weather variability and travel behaviour - what do we know and what do we not know. Submitted to *Transport Reviews*.

MY CONTRIBUTION TO THE PAPERS

The idea of paper I was initiated from joint discussion between Professor Yusak Susilo and Chengxi Liu. Chengxi Liu prepared the dataset, run the model, and wrote the paper. The supervisors helped very much in revising Chengxi' writing, interpreting the results and in responding reviewers' comments until the paper was accepted.

The idea of paper II was initiated from joint discussion between Professor Yusak Susilo and Chengxi Liu. The model structure was adopted from Susilo and Kitamura (2008). Chengxi Liu prepared the dataset, run the model, and wrote the paper. The supervisors helped very much in revising Chengxi' writing, interpreting the results and in responding reviewers' comments until the paper was accepted.

The idea of paper III, V, VI and VIII was initiated from joint discussion between Professor Yusak Susilo and Chengxi Liu. Chengxi Liu prepared the dataset, run the model, and wrote the paper. The supervisors helped very much in revising Chengxi' writing, interpreting the results and in responding reviewers' comments until the paper was accepted.

The idea of paper IV was from Chengxi Liu. Chengxi Liu programmed the model, and wrote the paper. The supervisors helped very much in revising Chengxi' writing, interpreting the results and in responding reviewers' comments until the paper was accepted.

The idea of paper VII was initiated from joint discussion among Professor Yusak Susilo, Chengxi Liu and Nursitihazlin Ahmad Termida. Nursitihazlin Ahmad Termida prepared the dataset. Chengxi Liu developed and run the model, and wrote the paper. The supervisors helped very much in revising Chengxi' writing, and interpreting the results.

RELATED PUBLICATION, NOT INCLUDED IN THIS THESIS

IX. Susilo, Y. O., Liu, C. (2015). The influence of parents' travel patterns, perceptions and residential self-selectivity to their children travel mode shares. *Transportation*, 43(2): 357-378. doi:10.1007/s11116-015-9579-0

X. Liu, C., Susilo, Y.O., Dharmowijoyo, D.B.E. (2015). Investigating inter-household interactions between individuals' time and space constraints. Paper presented in 14th International Conference on Travel Behaviour Research (IATBR) in Windsor, 2015.

XI. Cats, O., Abenoza, R.F., Liu, C., Susilo, Y.O. (2015). Evolution of Satisfaction with Public Transport and Its Determinants in Sweden: Identifying Priority Areas. *Transportation Research Record: Journal of the Transportation Research Board* 2538: 86–95

XII. Susilo, Y. O., Liu, C., Börjesson, M. (2016). Activity-travel pattern of different generations of Swedish women. Paper submitted to *Transportation Research Part A*.

XIII. Liu, C., Wang, Q., Susilo, Y. O. (2016). Assessing the impacts of collect-delivery points to individual's activity-travel patterns: A greener last mile alternative? Paper accepted for presentation in 14th World Conference on Transport Research (WCTR) in Shanghai, 2016.

XIV. Sun, Y., Liu, C., Chen, Y., Susilo, Y.O. (2016). The effect of residential housing policy on car ownership and trip chaining behaviour in Hangzhou, China. Submitted to *International Journal of Environmental Research and Public Health*.

XV. Susilo, Y. O., Liu, C., Börjesson, M. (2016). How policies and values have changed activity-travel participations across gender, life-cycle, and generations in Sweden over 30 years. Paper submitted to *Transportation Research Part A*.

XVI. Susilo, Y. O., Liu, C. (2016). Exploring the patterns of Time Use and Immobility in Bandung Metropolitan Area, Indonesia. Paper accepted for presentation in American Geographer Annual Meeting (AAG) in San Francisco, 2016.

The author's contribution in those publications except XI, was in data preparation, modelling effort and writing the draft paper. The author's contribution in XI was in modelling effort.

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1 INTRODUCTION

1.1 Climate change and travel behaviour

The period of the last three decades is likely to be the warmest three decades of the last 1400 years in the Northern Hemisphere. According to American National Centers for Environmental Information (NOAA, 2015), July 2015 was the warmest month ever recorded for the globe, as shown in Figure 1. Together with such a tremendous global warming phenomenon, extreme weather conditions are becoming more frequent. In 2015, heavy snowfall in the eastern coast of U.S., and heavy rain at the world's driest dessert, Chile's Atacama Desert, those extreme weather events cause huge loss in world's most densely populated metropolitan areas as well as world's most depopulated areas.

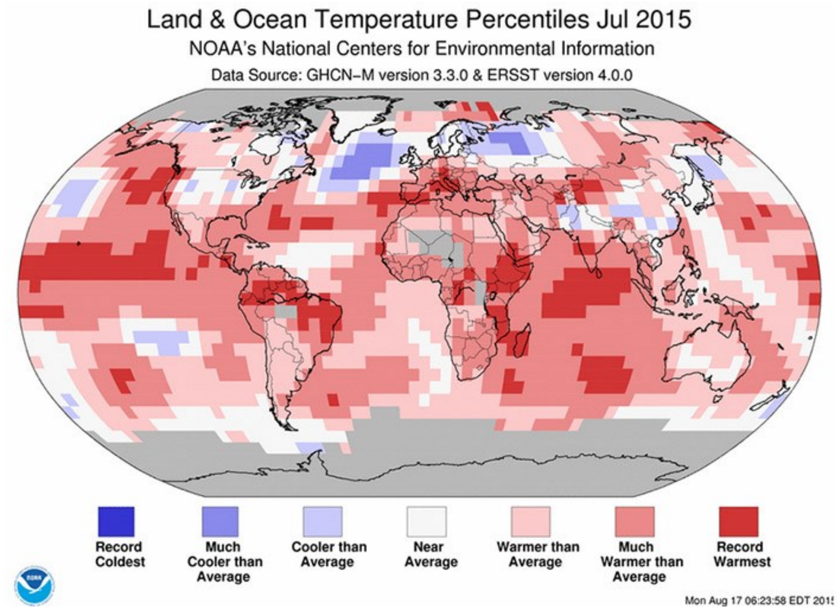

Figure 1 Temperature percentiles recorded in July 2015 (NOAA, 2015)

On the other hand, transport system is one of the main contributors to climate change. Transport is one of the major emitting sectors and the only sector that continues to grow substantially (European Commission, 2015). Overall, the transport sector produces the second largest share of CO_2 emissions among all sectors in the EU, in which road transport, mainly by passenger car, is responsible for around 70% of the total CO_2 emissions in the transport sectors (EU Transport in Figures, 2014). There is no doubt that human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems (IPCC, 2016).

To the transport system, extreme weather events can cause critical failures at major transport hubs and lead to disruptions of the whole transport system (e.g. Lam et al., 2008; Fu et al., 2014). However, climate change and the change of everyday weather can also lead to a gradual change of individual travel behaviour, thus lead to a gradual change in travel demand (Koetse and Rietveld, 2009). In fact, the impact of everyday weather on transport system, although is less noticeable than that of extreme weather events, can have a strong influence on the transport system, since the variation of everyday weather influences the travel patterns of each traveller throughout the year while extreme weather may only affect a sub-region and its impact may only last for a short time period. Understanding the change of travel behaviour given climate change and the change of everyday weather is enormously important. As a change of everyday weather may correspond to a marginal change in travel behaviour, those changes in travel behaviour would result in a fluctuation of travel demand in different weather conditions, and thus contribute to various transport externalities, congestion, emission and traffic safety, etc. Therefore, considering weather in travel behaviour studies can enhance the understanding of how people travel across space and time. Incorporating weather elements in travel demand models can improve the accuracy and prediction power of travel demand forecasting, thus increase the robustness of decision support system for urban planning and transport policies. Furthermore, given the warmer future climate, long term travel demand forecasting without considering the impacts of climate change can potentially over/under-estimate the future travel demand, thus may result in misleading policy implications.

From a microscopic point of view, modelling travel behaviour with weather effects replies on plausible assumptions on travel decision making mechanism, including how travel behaviour should be modelled and how weather should be represented in travel behaviour models. One the one hand, it is widely recognized that travel is a derived demand; derived from the need to pursue activities distributed in space (Axhausen and Gärling 1992). Activity-based models try to model travel behaviour as a result of activity participation and activity sequencing. Modelling weather impacts in an activity-based model framework can better reveal the actual roles of weather on travel behaviour than modelling weather impacts in a trip-based modelling framework. However, existing weather studies on travel behaviour mostly adopted a trip-based model framework.

On the other hand, weather in most existing travel behaviour studies is represented as a series of objective variables, e.g. temperature, precipitation, relative humidity, etc., and each has a single effect (see review: Böcker et al., 2013a). However, weather is fundamentally a 'subjective' perception rather than an objective measure that affects individual's everyday travel decisions (e.g. Thorsson et al., 2004; Knez et al., 2009). Objective weather variables in combination generate a micro-thermal environment and such an environment is perceived by a given individual with a specific socio-demographic profile. In travel behaviour research, only few studies used combined weather variables to represent the thermal environment (one example: Cremmers et al., 2015), while almost no studies used subjective weather measures. Different weather representations in travel behaviour modelling can affect the spatial transferability of the modelling results. For instance, the estimated effects of objective weather variables from studies conducted in tropical countries may not be transferrable to those from studies conducted in Nordic countries. Using subjective weather perception measures may help explain the spatial heterogeneity of weather effects, since subjective weather measures already take into account individuals' "indifference weather condition" as the reference point while the individual heterogeneity on weather perception that contributes to the problem of spatial transferability is mostly reflected and captured in the heterogeneity of reference point in relation to observed weather variables. For instance, 20 °C may be perceived cool for an individual from Indonesia who gets used to tropical climate, while 20 °C may be perceived warm for an individual from Sweden who rarely experiences hot climate. This heterogeneity in terms of weather reference point may lead to differences in the effects of objective weather measures on travel behaviour, but can be captured when using subjective weather perception measures.

Furthermore, most existing weather related studies focus on travel behaviour and travel demand, while little attention is paid to the related transport externalities, such as emissions, traffic safety, health effects, etc. Since weather does correspond to the change in travel behaviour and travel demand, it is expected that the transport related externalities are also influenced by the change of weather and climate. Deriving the marginal effects of weather and climate change on externalities is essential for policy makers to better assess transport policies related to those externalities.

With these research gaps in mind, this thesis reflects an investigation of the effects of weather and climate on individuals' activity participation and travel behaviour in a holistic way. This research aim is further decomposed into four main research questions in this thesis:

1) How large are the spatial variations of the effects of objective weather variables on activity travel patterns?
2) What are the effects of weather on activity participations and travel behaviour considering travel as a derived demand of activity participation?
3) What are the roles of subjective weather perception and the heterogeneity of individual reference point of weather perception?
4) How large are the changes in transport externalities due to the climate change?

As this thesis has been submitted in the form of a PhD Thesis by Publication, a large proportion of the content included is in the form of research articles that have already been accepted or submitted for publication. This introductory chapter provides an overview of those publications and how those publications fit together to answer the research questions listed above.

1.2 Research objectives

The thesis utilizes two data sources. The first one is the Swedish nation travel survey (NTS) with data ranging from 1994 to 2011 (Algers, 2001), matched with weather data from the Swedish meteorological and hydrological institute (SMHI). The daily measured and three-hour measured weather data was assigned to each trip by matching the weather data from the weather station nearest to the departure point of the trip and selecting the weather variable with the measured time closest to the departure time. The average distance from the weather station to its corresponding city centre is around 10 km. The limitation for combining two datasets is that distances from a nearest weather station to respondent's departure place vary for each trip, raising questions about to which degree weather conditions measured at weather station are the same as those at the departure place. However, if the travel behaviour variables of interest are in daily level (mostly in all eight papers), the effect of these uncertainty and variability are reduced. Compared to other similar studies, the NTS data combined with SMHI weather data cover a longer period and broader region, 1994 to 2001, 2003 to 2004, 2005 to 2006 and 2011, throughout all Sweden's regions. This advantage enables us to explore weather impacts more deeply in both space and time dimensions.

The second dataset applied in this thesis is a longitudinal travel survey data collected in Solna municipality, Stockholm. The survey used a self-reported two-week travel diary via paper and pencil in four waves. The implementation of this panel survey covered an overall length of seven months starting from October 2013 to June 2014. The first wave (14th-27th October, 2013) travel survey took place just before the opening date (28th October, 2013) of the new tram line extension. The following waves took place afterwards. In this thesis, only the travel diary data from third (17th-30th March, 2014) and fourth (26th May-8th June, 2014) waves were used which are 5 months after the opening date of the tram line extension. Thus the influence of the newly extended tram line on individuals' travel behaviour change was believed negligible. Besides, no major infrastructure change took place from wave 3 to wave 4 periods. Moreover, this seven-month period minimises an issue of sample aging when implementing a panel survey (Raimond and Hensher, 1997). Totally 67 individuals participated in all waves and 75 individuals participated in wave 3 and wave 4. Detailed description of this panel survey can be found in Termida *et al*. (2016). In this survey, two weather related questions were asked for each respondent every day during these two-week survey periods. The first one is: *how did the weather make you feel on the given day*? A 5 point Likert scale measure ranges from "*very disappointed*" to "*very satisfied*". Another issue is that each weather question was answered once per day as it was attached in the travel diary survey. Thus subjective weather perception was only available at daily level. Although the weather perception surely varies in different time of a day according to the weather condition at the given time of a day, it is practically difficult and expensive to obtain the subjective weather perception multiple times in a day. However, given the fact that subjective weather perception is typically qualitative and ordinal, it is assumed that the obtained Likert scale score represents the respondent's perception of the overall weather on the given day. Thus, the subjective weather perception at daily level can still be interpreted as the subjective feelings towards weather in an overall day.

To answer the research questions, a series of research objectives are discussed and addressed in the publications.

Research objective 1: to examine spatial and temporal heterogeneity of the effects of objective weather variables in activity participation, mode choice and trip chaining. (Paper I, Paper III and Paper V)

Paper I aims to examine the impacts of objective weather variables on individuals' mode choice in different regions of Sweden with different climates. Paper III explores the interactions between time allocation, travel demand and mode choice under different weather conditions in different regions of Sweden. Paper V focuses on the impacts of weather on trip chaining complexity and adopts a spatial expansion method to account for spatial heterogeneity between municipalities. Understanding these would be crucial in producing a better understanding and forecasting the travel demand within the transport network and in determining the most suitable transport policy that can be implemented during particular weather conditions for particular geographical locations in particular seasons.

Research objective 2: to examine the weather impact and the climate impact when several activity-travel variables are jointly modelled. (Paper II, Paper III and Paper IV)

Paper II aims to analyse the impacts of weather variability on the individual's daily activity-travel engagement, including activity time use, trip frequency, trip chaining, travel time and mode share. Paper III adopts a similar model structure but focuses more on the non-commuters who are found to be more elastic to the change of weather and climate. Paper IV develops a multivariate sample-selection model to model activity time allocation problem. Modelling activity participation and travel behaviour jointly provides a more comprehensive insight into weather and climate impacts than studies that only focus on one activity-travel variable.

Research objective 3: to understand the role of subjective weather perception and the heterogeneity of individual reference points of weather perception. (Paper VI)

Paper VI aims at exploring the heterogeneity in the reference points of weather perception for individuals from different socio-demographic groups, and exploring the role of subjective weather perceptions affecting individuals' leisure activity participation decisions. Exploring how individuals perceive weather and utilizing their weather perception in travel choices is essential to better understand the underlying reason of spatial and temporal heterogeneity of weather effects.

Research objective 4: to estimate the marginal change of externalities due to the change of weather and climate. (Paper VII)

Paper VII adopts a model structure to model the impacts of weather and also considers the impacts of weather on emission factors of vehicles. The marginal effects of weather on transport CO_2 emissions are derived and the results can be useful in emission policies and cost-benefit analysis.

Research objective 5: to provide a summary and assess the methodological issues on modelling weather in travel behaviour studies. (Paper VIII)

Although the research questions listed above will be addressed in this thesis, the results shown above also propose further research questions. Therefore, Paper VIII summarizes the existing findings in relations between weather variability and travel behaviour, and critically assesses the methodological issues in those studies. Several further research directions are identified and suggested for bridging the gap between empirical evidence and current practice in cost-benefit analysis.

2 THEORETICAL BACKGROUND

2.1 The representation of weather in travel behaviour studies

2.1.1 Weather variables as objective measures

So far most of the previous studies have investigated the relationship between objective weather measures and travel behaviour variables. The spatial and temporal matching between the weather information and the observed trips is often the first research question aroused in the data preparation stage. Most studies assigned weather information to each trip by matching the meteorological indicators from the weather station closest to the departure point of the trip and selecting the weather variable with the measured time closest to the departure time. By doing this, it is implicitly assumed that each traveller would base his or her travel decision on the weather condition that is prevailing at the departure place and time. In many cases, weather stations that record weather information can be sparse relative to the spatial distribution of trip occurrence. Therefore, various interpolation methods have been used to assign the most "accurate" weather information to each trip occurrence location by assuming a certain spatial distribution of the meteorological indicators. For instance, Chen and Mahmassani (2015) interpolated a smooth function over the study area based on the observed meteorological indicators at the stations. Jaroszweski and McNamara (2014) employed a weather radar approach, though their focus is on traffic accidents. Nevertheless, the use of different interpolation methods is to better reflect the actual weather condition at a given specific location.

Another issue is whether to match the weather information to the departure time and location, arrival time and location, or a certain period of time during the trip. Chen and Clifton (2011) argued that travellers would assess the weather conditions based on the conditions prior to travel. Chen and Mahmassani (2015) assumed travellers would consider the weather conditions that are in a near future, and they matched weather data according to the destination location and time of each trip, although they also admitted that "more research is needed to examine how weather is incorporated in travel decision processes". Based on a stated preference survey, Cools and Creemers (2013) showed that "planned" travel decisions are often altered by a last-minute change in response to adverse weather conditions at the time of departure. Sihvola (2009) interviewed the car drivers and also found a substantial amount of drivers changing travel plans (e.g. change route or departure time). Those findings do not suggest a uniform solution but point out the need for deeper understanding of the role of weather in the travel decision making process.

Weather information from weather stations is often in the form of meteorological measures such as max/min/average temperature, wind speed, relative humidity and precipitation, etc. Those meteorological measures are often directly adopted into the travel behaviour studies in representing weather (Böcker et al., 2013a). This implicitly assumes that each meteorological indicator has a single and independent effect on the travel behaviour indicator of interest. However, different meteorological measures often co-occur, indicating that the effect of each meteorological measure on travel pattern is interrelated. Phung and Rose (2008) found a combined negative effect of wind and light rain on bicycle counts. A few weather studies in travel behaviour used data mining techniques to classify distinct weather types. For instance, Clifton et al. (2011) used a two-step clustering technique to classify various types of weather conditions based on observed meteorological indicators. Creemers et al. (2015) pioneered weather related travel behaviour studies by introducing different thermal comfort constructs and comparing their performance in travel behaviour models. However, machine learning methods to classify weather types and thermal comfort measures have not been widely used in most travel behaviour studies related to weather.

2.1.2 Weather variables as subjective perceptions

Despite the fact that the concept of perceived weather conditions have been used in many psychological studies (e.g. Thorsson et al., 2007; Thorsson et al., 2011; Connolly, 2013), subjective weather perception measures are rarely introduced in travel behaviour studies. Böcker, et al. (2015) included a measure of perceived temperature and showed that weather-exposed cyclists experience thermal conditions as significantly colder than the more weather-protected users of motorised transport modes. Subjective weather measures have several theoretical advantages compared to objective weather measures. Weather is fundamentally a subjective perception that is perceived by an individual and used in his/her travel decision making process. Individuals with different socio-demographics, social-cultural contexts, can have different subjective weather perceptions even under the same weather conditions (Knez et al., 2009). Theoretically, using subjective weather perception provides more accurate and interpretable weather effects than using objective weather measures, since the subjective weather measures naturally define an individual's reference point of his/her perceived weather, which is usually latent/unobserved when objective weather measures are used. The subjective weather measures serve as mediation factors to bridge objective weather measures and travel behaviour. The relationship between objective weather measures and subjective weather measures reveals the individual heterogeneity in perceiving weather. The relationship between subjective weather measures and travel behaviour reveals the roles of weather in one's travel decision making process.

Subjective weather measures are also believed to be interrelated with other psychological constructs such as moods and happiness. Psychologists tend to explore the role of weather on well-being while treating travel patterns as mediating effects (see reviews, Kööts, et al., 2011), but travel behaviour analysts tend to explore the role of weather on travel patterns while treating well-being as control variables. After all, it is plausible that the relationships among weather, psychological constructs and travel behaviour are mutually interacted. One's travel behaviour is not only influenced by weather but also affects his/her subjective weather perception (e.g. one who is immobile on the given day may not experience the outdoor weather and thus is more likely to have a neutral subjective weather perception on that day). Understanding these complex relationships would be vital for capturing the actual role of weather on travel behaviour and thus improving the prediction power of travel demand forecasting in a possible warmer future climate.

2.2 The spatial and temporal variations of weather effects

2.2.1 The spatial variation of weather effects

When objective weather measures are used in travel behaviour models, as in most empirical studies, it is often stated as "the results from this case study may not be transferrable to other countries, regions". This spatial variation of weather effects on travel behaviour can be attributed to various reasons, such as geographical difference, climate difference and population difference, etc., for any two different locations.

Weather conditions and built environment are intrinsically interrelated and together form the microclimate at a specific location (Theeuwes, et al., 2014). Compared to natural areas, densely built urban areas cool less effectively at night due to heat stored in building surfaces and reduced radiation into the open sky, while warming up more quickly during the day due to multiple reflections of solar radiation, heated building surfaces, and a lack of evapotranspiration from green plants, although the warming up may be counteracted by building shadows (Böcker, 2014). Therefore, individuals travelling over space-time in areas with different built environments may experience different microclimates even with the same meteorological measures, thus lead to different travel decisions. From a macro level point of view, cities and regions with distinct built environment characteristics may exhibit clear weather effects as distinct microclimates are formed and perceived by travellers.

The effects of weather on travel behaviour may also differ between countries with distinct climate and culture, and therefore are climate and culture dependent. Local residents in countries with distinct climate and culture may adapt their clothing type, lifestyle, activity participation and travel behaviour to the local climate according to the culture and social norm, thus they may response differently to a change of a weather variable in different variable intervals. For example, in Scandinavia, cold weather and short days limit the time spent outdoors during large portions of the year. In Tokyo, Japan, however, cold weather is seldom a problem. Meanwhile, the Scandinavian ideal of beauty has included a suntan, whereas in Asia, the ideal of beauty is fair skin. The above examples can explain the fact that most people in northern Europe automatically choose a place in the sun, whereas Japanese people tend to avoid the sun to a greater extent (Thorsson et al., 2007).

Different population structure may also contribute to the spatial variation of weather effects. Individuals with different socio-demographic profiles may have different space-time constraints (Hägerstrand, 1970) and health conditions due to individuals' different personal and social roles. E.g. elders may have more free time but are limited by their physical abilities, and thus they may not respond to a good weather. On an aggregated level, the impact of weather in a region with an aging population would therefore differ from that in a region with a young population.

2.2.2 The temporal variation of weather effects.

Even for a given region, the weather effects may not be the same in different time of a year. For instance, 10°C in summer in a Nordic country may have a completely different effect as 10°C in winter in that country. The former may be interpreted as "cold in summer" while the latter may be interpreted as "warm in winter". This is because individuals have different weather adaptations and different standards (reference point) of "comfort" weather in different seasons. Hassan and Barker (1999) were among those who first tried to investigate the unseasonable weather impact on traffic. They defined the unseasonable weather as those with largest difference between observed and historically mean weather variables. Sabir (2011) used seasonal dummies together with objective weather variables in the travel behaviour model and found significant effects of seasonal dummies. These findings indicate that the estimated variable effects of weather may be different in different seasons.

On the other hand, the weather effects for a given region may also differ in different years, since the climate is changing dynamically so as people's weather adaptation and reference points of subjective weather perception. In Sweden, the seasonal mean temperature and precipitation have increased continuously from 1994 to 2011. It is plausible that Swedish citizens are gradually adapting to the new climate reflected in the change of their travel behaviour, although the magnitude may be small.

2.3 The dynamic and multi-dimensional nature of travel behaviour

The travel choices are often made jointly, which indicates a complicated travel decision making process. For instance, trip chaining choice is often made jointly with mode choice which is subject to the destination of each trip in the trip chain. Those who choose to drive a car are more likely to do complex trip chaining and visit distant destinations (Ye et al., 2007). Travel choices are often treated and modelled as conditional choices subject to the activity participation choices, including activity location choices (e.g. Bhat and Singh, 2000), activity timing (e.g. Habib et al., 2009), and activity duration (e.g. Lee, et al., 2009), etc. Travel choices are also referred to short term choices and are subject to the long term choices such as car ownership and residential location choices (e.g. Cao et al., 2007 and Noland, 2010). Recently, Zhang (2014) also argued that people's long term life-cycle choices would be a long term choice relative to residential location choice and car ownership choice.

To model activity participation and travel choices, model frameworks that can handle multiple dependent variables of different types (categorical, continuous, counts etc.) are needed. Moreover, given the dynamic nature of activity participation, models that can handle state dependence are also discussed. The next subsections focus on summarizing the methodological issues on modelling activity travel variables.

2.3.1 The instrumental variable technique

Instrumental variable technique (IV) is used extensively in capturing the endogeneity effect of residential location on travel behaviour (see review: Mokhtarian and Cao, 2008). A simple model with two dependent variables, y_1 and y_2, with one as the instrumental variable can be expressed as:

$$y_1 = f(X_1) + \mu$$
$$y_2 = g(\widehat{y_1}, X_2) + \varepsilon \quad (1)$$

In the equation above, the equation of y_1 first models y_1 as a function of instrumental variables X_1. It is assumed in IV models that X_1 is not correlated with ε. The equation of y_2 then is modelled as a function of exogenous variables X_2 and the predicted value of y_1, $\widehat{y_1}$. Since X_1 is by assumption uncorrelated with ε, the predicted value $\widehat{y_1}$.as a function of X_1 is also uncorrelated with ε. IV technique is often used to model continuous dependent variables but very few in modelling discrete dependent variables (Bhat and Guo, 2007). Lee (2007, 2009) used a Tobit model with IV to examine the determinants of activity time allocation and the relationship between activity duration and travel time. In weather related travel behaviour research, the IV technique can be a useful approach, since weather can potentially be variables in X_1 which serve as instrumental variables. For instance, weather can affect travel time to shopping (y_1) (e.g. due to the change of travel mode, etc.) thus leading to a change in shopping duration (y_2).

However, the limitation of IV technique is also well-known. The requirement of IV is in itself a contradiction. First, $\widehat{y_1}$ must not be significantly correlated with ε. Second, $\widehat{y_1}$ must be significantly correlated with y_1 to control for endogeneity. However, not only finding suitable X_1 with which to model y_1 can be difficult, but also modelling y_1 as a function of X_1 which is uncorrelated with ε will necessarily leave a substantial amount of variance in y_1 unexplained, therefore making $\widehat{y_1}$ less correlated with y_1 (Mokhtarian and Cao 2007). Such limitation may potentially yield inconsistent estimation in IV model.

2.3.2 The multivariate modelling and sample selection model

IV, although is computationally simple, has its limitation as discussed above (difficult in finding perfect IV and not applicable when the dependent variables are discrete). The sample selection model (Heckman, 1990) is often used as an alternative approach, although is more computationally demanding. A typical sample selection model can be expressed as:

$$y_1^* = f(X_1) + \mu$$
$$y_1 = 0 \text{ if } y_1^* < 0;\ y_1 = 1 \text{ if } y_1^* \geq 0$$
$$y_2 = g_1(X_2) + \varepsilon \text{ if } y_1 = 0 \quad (2)$$
$$y_2 = g_2(X_2) + \varepsilon \text{ if } y_1 = 1$$

The equation of y_1^* is often called selection model. In Eq.(2), the selection model has a binary outcome, either 1 (e.g. choosing to travel by car) or 0 (e.g. choosing not to travel by car). However, the selection model can have a multinomial outcome (e.g. choosing among walk, bike, car and public transport) or an ordered outcome (e.g. number of trips travelled in a given day). The parameters and functional form of the outcome model, y_2, is dependent on the outcome of the selection model, y_1. It is worth noting that if all variables in X_1 do not appear in X_2, such a sample selection model is essentially an IV model.

The sample selection part can be extended into a multivariate case. In that sense, the selection model is not one equation, but multiple equations set up jointly. For instance, the selection model can be three equations of binary activity participation, whether to play football on a given day, whether to go to gym on a given day and whether to go shopping on a given day. Each selection model is associated with an outcome model, the activity duration of football/gym/shopping on that day. The multivariate sample selection model not only captures the sequential nature of activity participation and travel which is specified by sample selection, but also captures the interdependencies and trade-offs in activity participation with different purposes as specified in the multivariate modelling. In the context of weather related travel behaviour studies, weather can potentially affect the activity participation and time allocations, e.g. reducing the number of outdoor leisure activity trips and outdoor leisure activity time in bad weather condition, which may therefore increases the time spent on in-home leisure activities (multivariate nature of activity participation). This would therefore decrease the travel time for outdoor leisure activities (the outcome model of a selection model of outdoor leisure activity participation). Adopting this modelling framework would provide more precise and realistic marginal effects and elasticities of variable effects compared to models with one single dependent variable (Louviere et al., 2005).

2.3.3 The dynamic nature of activity travel patterns

Activity participation, especially non-mandatory activity participation shows a clear dynamic nature. A dynamic travel behaviour model will use time as a dimension and travel choices at a given point in time will be dependent on earlier conditions and events. The previous activity participations that influence the current activity participation decisions are often known as state-dependence or habit persistence (e.g. Ramadurai and Srinivasan, 2006; Arentze and Timmermans, 2009). For instance, if one has a habit of going to gym, observing this individual being in the gym on previous days would plausibly have a positive effect on observing this individual being in the gym on the given day. On the other hand, if one is an elder, observing this individual being in the gym on previous days would likely to have a negative effect on observing this individual being in the gym on the given day.

When investigating the weather impact, it is expected that weather would have a more prominent effect on leisure (non-mandatory) activity participation which clearly exhibits the dynamic nature. Modelling weather in the dynamic model framework is important and essential for deriving precise and realistic effects of weather. However, in order to capture the dynamic behaviour, longitudinal data collection is required. Given that most weather related travel behaviour studies have used cross-sectional data, the dynamic nature is often ignored in the analysis, and therefore, the estimated effects of weather on leisure activity participation may be biased (e.g. the estimated effects of weather may be too low if a considerable amount of respondents had leisure activities on the previous days and thus they need to have a rest on the observed day).

2.4 Externalities of weather effects

The impacts of weather on travel behaviour have profound consequences on travel related externalities, including transport emissions, congestion, traffic safety, etc. For instance, if a considerable amount of travellers travel longer distances in a warmer future climate (Böcker et al., 2013b), more emissions from passenger transport are expected in such a future climate. A more realistic behavioural model on activity participation and travel are the foundations of accurately assessing transport externalities. However, despite plenty evidences of the impacts of weather on travel demand, the traditional travel demand-supply models (four-step model) which often serve as a main tool in transport appraisals for calculating the transport externalities often do not consider the demand variation due to changes in weather. As the models are calibrated by travel survey data in which both good weather and adverse weather conditions are sampled, the predicted or simulated travel choices are neither interpreted as travel choices in good weather nor as travel choices in bad weather, but a kind of average of travel choices in good and bad weather depending on the proportions of samples under good/bad weather. The corresponding aggregated measures from the models, e.g. mode share and Origin-Destination demand, are also not aggregated measures in good/bad weather.

Although most of the travel demand models focus more on peak-hour traffic or commute trips which are less affected by weather, many of those models also modelled leisure trip demand (for instance, Sampers in Sweden, Algers et al., 2009). However, to what extent the model components of leisure trip demand are biased due to the absence of weather is largely unknown, so do the policy evaluations related to those modelled leisure trips. This calls for a need to utilize the knowledge gained in weather related travel behaviour studies and apply them in travel demand forecasting and externality assessment. The knowledge would help transport planners and policy makers better understand the relevant externalities that are due to the change of weather and climate.

3 CONTRIBUTIONS

Although papers included in this thesis represent independent and stand-alone research articles, these papers follow a logical order. Figure 2 presents the common and distinguishing elements among paper I to VII. Paper VIII provides a review on the weather related topics. As shown in Figure 2, both objective and subjective weather measures are used in the articles. Paper I, II, III, IV and VII used meteorological measures, in which climate and weather effects are separated and the interaction effect between these two effects are also considered. Paper V used a thermal index, Universal Thermal Climate Index (UTCI), to represent the thermal environment. Paper VI adopted the subjective weather measure which is a 5 point Likert scale measure. Several modelling techniques are used. Benchmark models such as multinomial Logit model and ordered Probit model are used to explore the spatial variation of weather effects (Paper I and V), in which Paper I focuses on model choice while Paper V looks at trip chaining complexity. Instrumental variable technique and sample selection model are developed to model activity participation and travel behaviour jointly. The direct, indirect and total effects of weather variables are presented (Paper II, III, IV and VII). Activity duration, activity participation, trip chaining, mode choice and travel time are jointly modelled. Paper VI develops a dynamic ordered Probit model to capture the influence of previous days' leisure activity travel on the leisure activity travel on a given day. Paper VII builds upon the knowledge from previous papers and further derives the marginal effects of weather on passenger transport CO_2 emissions.

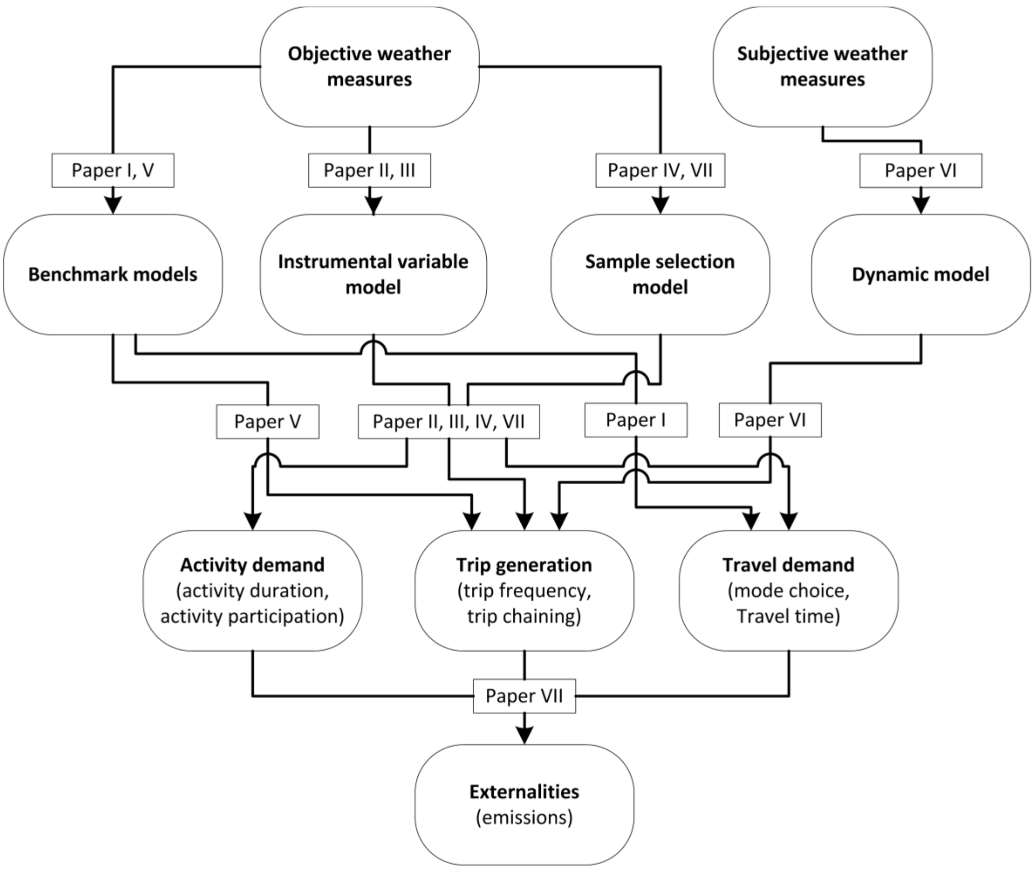

Figure 2. Overall linkage of research articles

3.1 The spatial and temporal variations of effects of objective weather measures

Paper I investigates the spatial and seasonal heterogeneity of the effects of objective weather measures on mode choice. 12 sub-models were estimated for each combination of seasons (spring, summer, autumn and winter) and regions (southern, central and northern Sweden). In general, the effects of weather variables differ in different seasons and different regions. The possibility of individuals choosing walk and public transport is higher in winter compared to summer, while the possibility of individuals choosing cycling is lower in winter compared to summer. Temperature effect is represented as a measure relative to the monthly mean temperature at a given municipality. People in the central and southern Sweden tend to walk less in abnormal (different than is expected on each corresponding season and region) temperature conditions in summer, while people in the northern Sweden tend to walk more in these situations. Northern travelers walk less when transformed temperature shifts from 'very cold' to 'very warm' but this is not the case in the central and southern Sweden. Similarly, northern Sweden cyclists are more aware of temperature variations than cyclists in the central and southern Sweden in spring and autumn when temperature changes significantly. Precipitation is negatively correlated with walk share in winter while surprisingly becoming positive in summer. One possible explanation for this observation is that precipitation also leads to a shortening of trip distance in summer. The results reveal the need of jointly considering several activity-travel indicators in a holistic model framework. The findings also highlight the importance to incorporate individual and regional unique anticipation and adaptations behaviours within our policy design and infrastructure management.

Paper III used the instrumental variable technique (Simultaneous Tobit model) to explore the regional difference of the effects of objective weather measures on non-commuters' activity-travel pattern. The model structure explicitly classifies activity-travel indicators into routine and leisure activity purposes and allows for mutually endogenous relationships between activity-travel indicators of those two activity purposes. Such a model structure depicts a more comprehensive picture of weather effects on individuals' activity-travel patterns on a given day compared to independent modelling of activity-travel indicators. The model results confirm that regional differences between weather effects are substantial due to differences in direct, indirect and total marginal effects. A regional difference observed in total marginal effects can be the result of different decompositions in direct and indirect marginal effects in different regions. For instance, the increase of monthly mean temperature has direct negative effects on routine activity duration and number of routine trips in southern and central Sweden. But those negative effects turn positive in northern Sweden. Between-municipality variability constitutes a considerable part of the variability in activity duration and travel time. Between-municipality variability in leisure activity duration and leisure travel time is larger in northern Sweden, while that of routine activity duration and routine travel time is larger in central Sweden, after weather and socio-demographic variables have been controlled.

Paper V focuses on the spatial and seasonal variation of the effects of the thermal index, Universal Thermal Climate Index (UTCI). Thermal index adopts existing knowledge in biometeorology and provides a combined effect of temperature, wind speed and relative humidity to represent the thermal environment given the weather condition. The results reveal that the variation of UTCI significantly influences trip chaining complexity in summer and autumn but not in spring and winter. The routine trip chains are found to be most elastic towards the variation of UTCI. The marginal effects of UTCI on the expected number of trips per routine trip chain range from -0.045 trips to 0.040 trips in summer and autumn in different municipalities, which indicates substantial spatial variations. There are clear differences in the marginal effect estimates between the model with weather variables and the model without weather variables. These differences in the marginal effects can reach 50 % and even higher. These findings also indicate that transport policies aimed at trip chaining behaviour must also be localised to incorporate the local climate.

3.2 Decomposing direct and indirect effects of weather

Paper II investigated the commuters' and non-commuters' activity-travel pattern using instrumental variable techniques. Non-work activity duration, number of trips and trip chains per day, travel time and mode share are jointly modelled within the Structural Equation modelling (SEM) framework. The analysis results show that the effects of weather can be even more extreme when considering indirect effects from other travel behaviour indicators involved in the decision-making processes. Commuters are shown to be much less sensitive to weather changes than non-commuters. Variation of monthly average temperature is shown to play a more important role in influencing individual travel behaviour than variation of daily temperature relative to its monthly mean, whilst in the short term, individual activity–travel choices are shown to be more sensitive to the daily variation of the relative humidity and wind speed relative to the monthly mean. Poor visibility and heavy rain are shown to strongly discourage the intention to travel, leading to a reduction in non-work activity duration, travel time and the number of trips on the given day.

Paper III focuses on the non-commuters and explicitly models the trade-offs between routine and leisure activity-travel pattern. The impacts of weather on the trade-off between routine and leisure activities are found. Weather effects are far from simple, strongly influenced by the mediation effects, especially with regards to travel time. A regional difference observed in total marginal effects can be the result of different decompositions in direct and indirect marginal effects in different regions. For instance, a colder-than-normal day has a positive direct marginal effect on leisure activity duration, but a negative direct marginal effect on leisure trips. This implies that although Swedish non-commuters have a tendency to travel less on a colder-than-normal day, they might spend more time per leisure activity. Similarly, a warmer-than-normal day has a negative direct marginal effect on leisure activity duration, but the effect is partially offset by the positive indirect marginal effect from routine activity duration.

These findings depict a more comprehensive picture of weather impact compared to previous studies and highlight the importance of considering interdependencies of activity travel indicators when evaluating weather impacts.

Paper IV develops a nested multivariate Tobit model which is a multivariate extension of a sample selection model. The model, instead of treating endogeneity effects as instrumental variables, models travel time as a sequential outcome conditional on the participation of activity. Compared to the instrumental variable models (Paper II and Paper III), this model framework is typically useful in prediction but not for revealing the heterogeneous pattern. The findings suggest a potential positive utility of travel time added on non-work activity time allocation in the Swedish case. Meanwhile, the results also show a consistent mode choice preference for a given individual. The estimated nested multivariate Tobit model provides a superior prediction, in terms of the deviation of the predicted value against the actual value conditional on the correct prediction regarding censored and non-censored, compared to mutually independent Tobit models. However, the nested multivariate Tobit model does not necessarily have a better prediction for model components regarding non-work related activities.

3.3 The role of subjective weather perception

Paper VI investigates the role of subjective weather perception. Two research questions are addressed. 1. How individuals from different socio-demographic groups perceive weather. 2. How subjective weather perceptions affect individuals' leisure activity participation decisions. The results show that the reference thermal environment in general corresponds to the historical mean of the thermal environment. The effects of objective weather measures on subjective weather perception vary substantially between individuals. Elders are more sensitive to the change of thermal environment, compared to teenagers, due to their physical conditions. Respondents from the household without children are in general more sensitive to the variation of the Z score of UTCI compared to those with children. The high income group is in general less sensitive to the variation of the Z score of UTCI compared to the low and medium income groups. Respondents with children in their households tend to have a much lower subjective weather scores in rainy conditions than those without children in their households.

Moreover, the effect of subjective weather perception on leisure activity participation is non-linear and asymmetric. Only "very bad weather" and "very good weather" significantly influence the leisure activity participation. The effect of "very bad weather" also varies significantly between individuals. However, this heterogeneity cannot solely be attributed to the socio-demographic variables, but more likely to be influenced by other unobserved social psychological factors. The intra-individual heterogeneity in the effect of "very good weather" has a smaller magnitude than that in the effect of "very bad weather". The intra-individual heterogeneity in the effect of "very good weather" can be explained mainly by socio-demographic variables, while the intra-individual heterogeneity in the effect of "very bad weather" cannot solely be attributed to socio-demographic variables but is more likely to be influenced by other unobserved social psychological factors.

3.4 The marginal effects of weather on passenger transport CO_2 emissions

Paper VII adopts the knowledge from the previous papers and explores the role of weather variation on passenger transport CO_2 emissions. Paper VII considers both the effects of weather on travel pattern and the effects of weather on vehicle emission factors. The marginal effects of weather on passenger transport CO_2 emissions are derived. The results showed an increase in individual CO_2 emissions in a warmer climate and in more extreme temperature conditions (5% CO_2 emission increase given 2 °C warmer climate and 20% more extreme weather), whereas increasing intensity of precipitation and snow corresponds to a slight decrease in individual CO_2 emissions, although it may be due to the fact that only a few trips were sampled in those weather conditions. Given that most large-scale transport demand–supply interaction models do not consider the impacts of weather variability, using the estimated CO_2 emissions from those models as the estimates of future external effects may considerably underestimate the actual future CO_2 emissions. With global warming and more frequent adverse weather conditions, such an underestimation may reach 8% or more.

4 SIGNIFICANCE OF FINDINGS

Understanding the roles of weather and climate on individuals' travel behaviour is essential for accurately predicting future travel demand in a possible warmer future climate. It would provide various implications on transport policies designed to incorporate the global warming and extreme weather events. To this extent, this thesis contributes to both the theoretical understanding on how weather affects individuals' activity-travel patterns and the practical implication on transport policies regarding to climate and weather mitigation. Specifically, this thesis focuses on the representation of weather and climate, travel behaviour modelling and externalities, in order to better depict how the changes of weather and climate can affect individuals' activity participation and travel behaviour.

In general, the findings in this thesis are useful for both policy-makers and researchers in the field of transport science, particularly in terms of travel behaviour and mobility. For researchers, this thesis provides further insights on how different weather elements jointly affect several travel behaviour variables by considering the direct, indirect and total effects. Besides, the understanding of the role of subjective weather perception provides further insights on how weather plays a role in the travel decision making process, compared to case-specific empirical assessment of the effects of weather. For policy makers, the regional difference of weather impacts found in this thesis highlights the importance of incorporating individual and regional unique anticipation and adaptations behaviours within our policy design and infrastructure management. The findings in Paper V also highlight the potential biasness of marginal effect estimates of other explanatory variables if weather effects are ignored, leading to potentially misleading policy implications. Findings in Paper VII show an increasing CO_2 emission in a future warmer climate, and the findings are useful for climate mitigation policies. Compared to previous studies that have investigated the impacts of weather on travel behaviour, this thesis provides deeper insights compared to previous studies from the following aspects.

By exploring the spatial and temporal heterogeneity of the impacts of weather on activity participation and travel behaviour, it is found that the impacts of weather and climate differ in different seasons and different regions for commuters and non-commuters respectively. The effects differ not only in terms of magnitude but even the sign of the effect. For instance, precipitation is negatively correlated with walk share in winter while surprisingly becoming positive in summer. Therefore, results from one specific region and time of a year cannot be directly adopted into another region and different time of a year. It is crucial to incorporate and anticipate the uniqueness of weather impacts for a given region and season within our policy design and infrastructure management. For instance, the travel demand of leisure activity travel is expected increasing in southern Sweden (marginal increase in number of leisure trips per individual per day is 0.31) and central Sweden (marginal increase in number of leisure trips per individual per day is 0.46) in snow covered situation, while the opposite is true in northern Sweden (marginal increase in number of leisure trips per individual per day is -0.54) (Paper III). Therefore, road maintenance on snowy days and after snowy days, especially for roads connecting to leisure activity facilities, is important in southern and central Sweden.

By using instrumental variable techniques (paper II and III) and sample selection model (Paper IV), the direct, indirect and total effects of weather variables on multiple activity travel indicators are estimated jointly. Paper II, III and IV are the first such studies to consider the endogeneity and indirect effects in weather related travel behaviour studies. The results reveal significant indirect effects of weather variables on travel behaviour variables. These indirect effects among activity time use, trip generation, trip chaining and mode share, all reveal that various activity travel choices are interrelated, and thus the impacts of weather variables on one travel behaviour variable can have a significant indirect effect on another travel behaviour variable. The results also reveal that the indirect effects of weather can consist of a large share in the total effects. Therefore, transport policies targeted for one travel behaviour indicator may not achieve the desired effect if considerable indirect effects from another travel behaviour indicator are not considered. For instance, results in Paper II suggest increasing travel demand and higher cycling share in a “warmer than normal” day in winter. A support infrastructure would be better in place to service the increased demand and keep the use of more sustainable and greener travel mode as long as possible. Paper II also highlights the importance of winter road maintenance especially in urban areas in southern Sweden where heavy snow situation was not as common as northern Sweden. Among those adverse weather factors, heavy rain, strong wind, bad visibility and snow, bad visibility is the one which has the most negative impacts on commuters’ activity participation (activity duration, number of trips and trip chains). For non-commuters, bad visibility and heavy rain are the two factors with similar impacts which most negatively influence the activity participation, then followed by the strong wind. Thus, an advanced preparation especially in foggy days and heavy rain conditions would be required to minimize the disruption due to the changes in travelers’ daily activity-travel patterns.

By utilizing the subjective weather perception measures (Paper VI), the reference dependency problem in the effects of weather variables on travel behaviour is addressed. The results show that the reference point (indifference weather condition) in general corresponds to the historical mean of the thermal environment. However, individuals with different socio-demographic profiles have different subjective weather perception under even the same weather conditions, mainly due to individuals having different perceptions on short term variations of thermal environment (deviation against its historical mean value). Furthermore, the effect of subjective weather perception measure also shows heterogeneous effects on leisure activity participation for individuals with different socio-demographic profiles. These two kinds of heterogeneity in subjective weather perception can potentially contribute to spatial and temporal variations of the impacts of weather as discussed above. Understanding how individuals perceive weather is one step further towards a better understanding of how weather affects individuals’ activity travel decision making process compared to empirical studies that directly link objective weather measures and travel behaviour variables.

By exploring the role of weather variation on passenger transport CO_2 emissions, it is found that the passenger transport CO_2 emissions would be higher in a warmer future climate with more extreme weather conditions. The emission of a possible scenario ‘mean temperature +4 °C, Z score + 50%, and precipitation + 20%’ according to IPCC future climate projection is calculated, which results in 4184.7 g per individual per day (108.1% of the base scenario, the current weather conditions). This means that CO_2 emissions will increase by 8% due to the changes in weather and climate in a pessimistic future climate scenario. This indicates that if a large-scale transport demand–supply model does not take into account weather elements, its prediction of CO_2 emissions in the future scenario can be significantly underestimated. Transport policies related to climate mitigation should either focus on market penetration of green vehicles (e.g. electric vehicle) in order to lower emission factors or cope with an increased travel demand, especially for long-distance car trips in Sweden, to decrease vehicle kilometres travelled.

5. LIMITATIONS AND FUTURE WORK

The time-geography framework can be incorporated to further understand how a local weather and infrastructure may form a particular micro-meteorological environment which is perceived by individuals living close to the particular area. Given different urban landscape and built environment features in different regions, the local thermal environment can be highly heterogeneous for two regions with different built environment and urban density but under the same weather conditions. Therefore, future research direction can focus on how local thermal environment is formed given the weather condition and urban form presented. In terms of modelling techniques, spatial dependent or locally weighted discrete choice models (Helbichet et al., 2014) can be applied to capture the combined effect of urban form and weather conditions.

The papers presented in this paper explored various aspects of the impacts of weather on individual's observed travel pattern. However, weather may actually act as constraints and affect individuals' accessibility and space-time prism (Hägestrand, 1970). For instance, adverse weather conditions may limit walking and cycling feasibility for a given individual (e.g. certain cycling lanes may not be functional on snowy days). Inferring the boundary of individual's travel in space and time requires observing multiday observation of individual's travel, while most existing studies used one-day travel diary. Space-time prism (e.g. Yamamoto et al., 2004) concept offers a general framework for analysing individual's ability and constraints travelling over space and time. Further studies incorporating multiday travel diary can help understanding how weather plays a role in affecting individuals' space-time prism.

In paper VI, the subjective weather perception is represented as one 5 point Likert scale measure. However, actual perception of weather may be multidimensional, e.g. the feeling of cold/warm, humid/dry, etc. adopting knowledge in biometeorology and psychology may provide further insights on how subjective weather perception should be measured.

Furthermore, weather may also affect various psychological constructs such as happiness and well-being, thus influences one's activity-travel choices. Measuring those psychological constructs and integrating them into weather related travel behaviour research would provide a more comprehensive picture of weather impacts. In terms of inference, integrating psychological constructs in travel behaviour models indicates introducing various latent variables into the discrete choice modelling framework, which is known as a hybrid choice model (Walkers and Ben-Akiva, 2002). Given the fact that subjective weather perception measure as a latent variable itself may also interact with those psychological constructs, it is challenging to get inference from hybrid choice models with multiple latent variables that are interacted with each other.

The papers presented in this thesis focus on individuals' travel behaviour. However, individuals' daily activities are often interacted with their household members'. Individuals with different roles in household may negotiate/share household activities. In that sense, weather may have different roles for different household members and affect the group decision making mechanism regarding distribution and allocation of household tasks to different household members (example of household travel choice behaviour: Zhang et al., 2009). Exploring this interaction given weather conditions forwards the current weather related travel behaviour research into household oriented travel behaviour analysis. The results would help understand to what extent weather would affect group decision making regarding activity distribution/negotiation within a household.

Finally, paper VIII shows that existing knowledge from weather related travel behaviour research is rarely adopted into cost-benefit analysis that is utilized as the main tool for transport appraisal, which indicates that the knowledge gained is not used in the practical decision making process of transport project selections. This is due to the fact that the traditional travel demand-supply models (four-step model) which serve as a main tool in transport appraisals often do not consider the demand variation due to changes in weather. Future research should focus on methodological issues in incorporating weather and climate in large scale travel demand models, as well as transport appraisal related issues such as future discounting, effect models, etc.

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