Chengxi Liu, Yusak O. Susilo, Anders Karlström

Quantifying the changes of travellers’ transport CO2 emissions due to the changes of weather and climate in Sweden

Chengxi Liu
Centre for Transport Studies
Department of Transport Science
KTH Royal Institute of Technology
Teknikringen 10, 100 44 Stockholm
Sweden
Email: chengxi@abe.kth.se

Yusak O. Susilo
Centre for Transport Studies
Department of Transport Science
KTH Royal Institute of Technology
Teknikringen 10, 100 44 Stockholm
Sweden
Email: yusak.susilo@abe.kth.se

Anders Karlström
Centre for Transport Studies
Department of Transport Science
KTH Royal Institute of Technology
Teknikringen 10, 100 44 Stockholm
Sweden
Email: anders.karlstrom@abe.kth.se


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Response to reviewers

First of all, the authors would like to thank the editor and three anonymous reviewers for their comments. The authors now revised the paper further according to the reviewers’ further comments. In the following paragraphs, the paragraphs with italic and red colour are reviewers’ comments. The paragraphs with black colour are authors’ responses.

Comments from Reviewer 1:

1 Corresponding Author
This is an interesting, well written and mainly well executed paper that looks at how the weather affects transportation CO2 emissions. It is relevant because a changing climate could be expected to also change activity patterns and emission factors.

The authors would thank reviewer 1 for his/her appreciation towards our work.

I particularly liked that the authors looked at both emission factors and activity. This is the place where I think the analysis could be strengthened, both graphically and in the text. Can you visually plot your results separating out these effect? When you state conclusions like precipitation and snow have little effect, is this because activity and emissions per km are working in different directions?

The authors appreciate reviewer 1’s suggestion of separating out the effects of changes in emission factors and the effects of changes in activity-travel. However, doing this is practically difficult. As the authors wrote in p. 4, line. 42, Eq.(1):

$$E_{total} = E_h + E_a + E_c + E_e = F_h \times D + F_a \times H + F_c + F_e \times D$$

The total emission of a trip in general has the form of emission factor ($F$) multiplying by a given activity-travel indicator ($A$), where $A$ can be distance, travel time etc.. Therefore, the change in total emission due to a change of weather ($\Delta E$) can be denoted as $\Delta E = (F + \Delta F) \times (A + \Delta A) - F \times A$, where $\Delta F$ and $\Delta A$ are changes in emission factors and changes in activity travel. By saying separating out the effects, one may be interested in knowing a function of $\Delta E = \alpha \Delta F + \beta \Delta A$, in which the effects $\Delta F$ and $\Delta A$ are separated and presented as $\alpha$ and $\beta$. However, as $\Delta E$ is not a linear function of $\Delta F$ and $\Delta A$ as shown above, such $\alpha$ and $\beta$ are interrelated and cannot be separated. In the models presented in this paper, there are many activity travel indicators ($A$) and different emission factors ($F$) associated to those activity travel indicators. The relationship between $\Delta E$ and $\Delta F/\Delta A$ are far more complicated than a linear relationship. Therefore, the authors do not separate these two effects.

However, the authors give the general trends of $\Delta F$ and $\Delta A$. One may get a general direction of $\Delta E$. For instance, if both $\Delta F$ and $\Delta A$ are positive, then the total emission will increase. For $\Delta F$, the authors added sentences regarding the sign of $\Delta F$ given changes in weather variables in p. 3, line. 21:

"Hot exhaust emission factor in general decreases with increasing temperature for both patrol and diesel cars and more so for diesel cars. Adverse weather such as precipitation and snow would trigger the use of in-vehicle air conditioning, wiper and window defrost and thus increases the hot exhaust emissions from auxiliary system. Cold start emissions are well-known to be larger in lower temperature conditions, while evaporative emissions increase with the increasing temperature."

The sign/effect of $\Delta A$ is shown in Table 2.
The authors should emphasize that the authors stated “increasing precipitation intensity and snow depth” have little effect, but not “precipitation and snow” have little effect. In Figure 1(b) and (c), the descriptive results showed clear difference in terms of emissions under no rain/snow and rain/snow conditions. However, as the authors stated in p. 18, line. 28:

“It is worth noting that only 30% of all sampled trips are under rainy conditions while only 8% are under snowy conditions. Therefore, changes of precipitation amount and snow depth would only affect the CO$_2$ emissions of those trips.”

Only a few observations were sampled in rain and snow conditions. Therefore, increasing precipitation intensity and snow depth may only affect those observations. The authors also wrote in p. 18, line. 30:

“However, it is plausible that the individual CO$_2$ emissions may increase/decrease more substantially if the heavy rain and thick snow situations become more frequent, for which this study does not consider.”

The authors do not consider changing more observations (trips) from no rain/snow condition to rain/snow condition, simply because in which locations and when there will have more rainy/snowy days are largely unknown. Although random drawing different observations and assigning a precipitation or snow depth may be an option, the estimated CO$_2$ emissions may inherit large variation.

The authors also agree that “activity and emissions per km are working in different directions” is another possible reason. The authors wrote in p.18, line.24:

“Although the precipitation amount is negatively related to the trip distance of urban local trips, see Table 2, its influence on CO$_2$ emissions is absorbed by the slightly more preferable usage of car mode in rainy days as well as the increase in emission factors in rainy days, mainly the factor of emissions from auxiliary system.”

Snow depth is an important variable. But wouldn’t most roads be cleared fairly rapidly? How do you account for this in your model?

This is exactly observed in our model. In Table 2(b), snow depth has insignificant effects on average speed of car trips and trip distance of non-work trips. This indicates that snow may not be an impeding on the road. However, snow depth may have an impact on the destination choice of non-work trips and mode choice (see Table 2(a)). It indicates that snow may not hinder the car travel but individuals may choose different non-work activities (such as skiing) in days with snow depth and thus different travel modes as well.

Figure 1(a) – it’s difficult to tell what is the effect of VKT changes, and what is the effect of emission factor changes. Can you separate these, out, or report the results per kilometer? For
example, in northern Sweden in the summer, I imagine vehicles are more efficient but emissions are much higher according to the graph.

Figure 1(a) reports the overall emissions per individual in different seasons and regions. It is worth noting that Figure 1(a) gives a more general picture of all travellers with all modes but not just car drivers. The authors have also added the emission per km according to season and region in Figure 1. As shown below

In general. The emission per km drive is highest in winter and then followed by spring. Northern Sweden has a higher emission per km than central and southern Sweden in general. As written in p. 3, line. 21:

“Hot exhaust emission factor in general decreases with increasing temperature for both patrol and diesel cars and more so for diesel cars. Adverse weather such as precipitation and snow would trigger the use of in-vehicle air conditioning, wiper and window defrost and thus increases the hot exhaust emissions from auxiliary system. Cold start emissions are well-known to be larger in lower temperature conditions, while evaporative emissions increase with the increasing temperature.”

So there is no surprise that northern Sweden in winter has the highest emission per km.

How do your nested models compare to a simpler linear model where VKT is the dependent variable? This would also be easier to interpret.

The authors agree that a simpler model with VKT is a much easier approach and especially easy for interpretation. However, such a simple model may lose generality and not be a good option for estimating emissions with future weather and climate. First, VKT is not the only activity-travel indicator influencing emissions. Indeed, VKT may be longer or shorter for a given trip in different weather conditions, the given individual may also change travel modes. He/she may also choose further/closer destination, resulting in different route choices (rural road/urban road/motorway).
If only VKT is considered as dependent variable, it is implicitly assuming individual would not change travel mode and would not change his/her route choice and would not travel more/less frequent in different weather conditions. As shown in Table 2, various activity-travel indicators are influenced by weather not only VKT, although VKT is also considered in this paper (in Table 2(b), travel distance for non-work trips). As shown in Figure 2, given the change of destination, the trip distance would be longer/shorter which would result in a change in mode choice, while the VKT is the trip distance of trips with car modes.

*I question the practice of eliminating some of the weather variables through backwards elimination, because these are what you are interested in. If the effect is zero, that should be shown in your results table and not be an assumption. It would allow the reader to distinguish between a large and noisy effect and no effect. As it is, there are some strange results – snow depth doesn’t affect the number of trips, for example?*

The authors agree that keeping all insignificant parameters in the model would be another alternative. The authors would list the pros and cons of these two alternatives (keeping/eliminating the insignificant parameters) as follow. Keeping the insignificant parameters is, as reviewer 1 said, good for interpretation and illustrating the roles of each weather variable, although eliminating the insignificant parameters do not hinder the interpretation either (one can just interpret those eliminated variables as having insignificant marginal effects). However, keeping the insignificant variables is not a good idea for the following scenario analysis, because insignificant parameters may then play a role in the estimated CO₂ emissions in each scenario. Readers may find it hard to interpret the results of scenario analysis because the increase/decrease in CO₂ emissions may be due to the significant marginal effects/parameters as well as the insignificant ones.

Nevertheless, eliminating insignificant parameters does not hinder the interpretation. An insignificant parameter indicates that the estimated parameter is statistically not different from zero. If the size of this insignificant parameter is small, it means this estimated value is by chance. If the size of this insignificant parameter is large, it may indicate there is not enough observation to capture this effect and the estimated effect may differ significantly from its true value (for instance the effect of snow depth on number of trips because only 8% trips were sampled in snow situations). In that case, including the insignificant parameter, which differs largely from its true value, would also strongly bias the results, although eliminating the parameter does the same. Therefore, the authors choose to eliminate insignificant parameters, mainly for the scenario analysis.

*I don’t understand this sentence: “It is worth noting that the change of CO₂ emissions in the scenario of a warmer climate and a more extreme temperature tends to be larger than the sum of changes of CO₂ emissions in each single scenario.” Do you mean more cold extremes?*

The extreme weather scenario refers to that “daily temperature Z score” increases by x%. and “daily temperature Z score” is separated into two intervals, “daily temperature Z score<0” and “daily temperature Z score>0”. Therefore, increasing “daily temperature Z score” by x% would
indicate that both those “daily temperature Z score<0” and “daily temperature Z score>0” cases would have a larger absolute value, which means that the observations (trips) have a both larger positive and negative Z scores. So it means both cold and warm extremes.

By saying this sentence, the authors mean that singling out the effect of “a warmer climate” and “a more extreme temperature” may underestimate the joint effects of these two. For instance, the individual CO2 emissions increase by 407 g in the joint scenario of “increasing monthly mean temperature by 5°C” and “increasing daily temperature Z score by 50%”, while the sum of the changes of individual CO2 emissions in each single scenario, scenario of “increasing monthly mean temperature by 5°C” is 282.7 g and scenario of “increasing daily temperature Z score by 50%” is 93.3 g, and the sum of these two single scenario is only 376 g (282.7 g + 93.3 g), which is smaller than the number in joint scenario, 407 g.

In p.18, line.17, the authors wrote:

“For instance, the individual CO2 emissions increase by 407 g in the scenario of increasing monthly mean temperature by 5°C and increasing daily temperature Z score by 50%, while the sum of the changes of individual CO2 emissions in each scenario is only 376 g (282.7 g + 93.3 g).”

Comments from Reviewer 2:

This paper is ambitious in trying to capture the impacts of the climate change on passenger’s transport behavior. It serves a useful purpose for practitioners and policymakers concerned with reducing the environmental impact of passenger related transport activity. The authors did test scenarios of how different climate change can affect emissions which is useful to agencies that want to develop polices for passenger industries to mitigate adverse impact. This paper can be improve by analyzing policy related to climate change in Sweden’s that how can passenger industries can reduce various emissions. Authors can also compare the result with other European countries.

The authors appreciate reviewer 2’s acknowledgement of our work. The authors now add several sentences regarding the policies related to climate change. However, the authors found it difficult to compare the estimated CO2 emission in the scenario analysis with the results from other European countries, because most existing studies in this field are descriptive. The authors did compare the CO2 emissions in the current climate and weather conditions in Sweden and that in Netherland and UK. In p.5, line.36, the authors wrote:

“On average, 3.73 kg of CO2 from passenger transport are emitted per individual per day in Sweden, which is slightly less than that from the Dutch study (3.8 kg of CO2 per person per day) that used Dutch national travel survey in 2005 and much less than that from UK study (4.3 kg of CO2 per person per day). However, given that study 8 did not consider CO2 emissions other than running hot exhaust emissions and did not consider weather in emission factors, it
is plausible that the difference between individual CO2 emissions in Sweden and that in Dutch/UK could be even larger.”

For policy related discussion, the authors added the following paragraph in p.19, line 20:

“The results presented in this study indicate the importance of considering weather and climate change in evaluation of CO2 emissions. Given that most large-scale transport demand-supply interaction models do not consider weather, using the estimated CO2 emissions from those models as the estimates of future external effects may considerably underestimate the future CO2 emissions. With the global warming and more frequent adverse weather, such underestimation may reach 5% or more. In cost benefit analysis, the underestimated external cost of CO2 emission would lead to a higher rank for projects with considerable environmental effects. Possible abatement could be to set up a higher marginal external cost for CO2 emission, higher than the shadow price for CO2 emission, in order to give a higher weight of CO2 emission per capital. For traffic management, the efforts then must not only cope with the seasonal and local weather pattern of activity-travel behaviour. For instance, more congestion in a warm summer day is expected. Therefore, appropriate congestion mitigation measurements are needed. Besides, long distance car trips are more preferred in warm months. Freeway management is needed in warm months to cope with the increasing demand.”

As an extension of this paper, the authors also have planned another paper focusing on the weather/climate related policy.

Comments from Reviewer 3:

Very interesting for those of us living in winter climate zones.

The authors agree that those living in winter climate zones may care more about weather. However, as emission problem is global, different estimates from countries in different climate zones are needed, and Meta cross-country comparison about climate impacts on CO2 emissions would be helpful.

Other minor issues:

After revision, this paper is a bit over the word limit, 7178 words without reference. If the editor believes the word limit should be strictly below 7000 words without reference, the authors can try to shorten the paper, although the authors do not recommend to do so.

Again, the authors would like to thank the editor and the reviewers for their positive supports and detailed comments. Should the editor and the reviewers have any further questions, we will be happy to provide further clarifications.
ABSTRACT

There have been a considerable body of studies on the relationship between daily transport activities and CO₂ emissions. But, how these emissions vary across different weather conditions within and between seasons of the year are largely unknown. Since individual activity-travel patterns are not static but vary across different weather conditions, it is immensely important to understand how the CO₂ emissions vary due to the change of weather. Using Swedish National Travel Survey data, with emission factors calculated through European emission factor model ARTEMIS, this study is a first attempt to derive the amount of CO₂ emission changes subject to the change of weather conditions. A series of econometric models were used to model travel behaviour variables that are crucial for influencing individual CO₂ emissions. The marginal effects of weather variables on the travel behaviour variables were derived. The results show an increase of individual CO₂ emissions in warmer climate and in more extreme temperature conditions, while increasing precipitation amount and snow depth shows limited effects on individual CO₂ emissions. It is worth noting that the change of CO₂ emissions in the scenario of a warmer climate and a more extreme temperature tends to be larger than the sum of changes of CO₂ emissions in each single scenario. Given that warmer climate and more extreme weather would co-occur more frequently in future, this result suggests even larger individual CO₂ emissions in such a future climate than expected.
1. THE CO₂ EMISSIONS OF PASSENGER TRANSPORT AND WEATHER

The European Union has committed itself to a 20% reduction of its greenhouse gas (GHG) emissions of which CO₂ emissions are the major quantity of interest, and transport is one of the main emitting sectors, and the only one sector that continues to grow substantially (1). Overall, transport sector produces the second largest share of CO₂ emissions among all sectors in EU, in which road transport, mainly the passenger car, is responsible for around 70% of total CO₂ emissions in Transport sectors (2). Measuring, modelling and predicting the CO₂ emission from road transport is thus an important and hot topic in transportation field. Researches on CO₂ emissions of road transport diverse between passenger transport (e.g. 3-4) and freight transport (e.g. 5-6). It is well known that two major factors determine the CO₂ emissions of passenger transport, the emission factor of the vehicle and the vehicle usage, vehicle mileages travelled.

The emission factor describes the amount of CO₂ emitted by a passenger car when the vehicle is being used per unit travel. The principle source of emission can be categorised into three types (7): 1. the “hot” exhaust emission: the amount of CO₂ being emitted during the use of the vehicle. 2. the cold start emission: the amount of CO₂ being emitted during each trip start when the engine does not reach its running temperature. 3. the evaporative emission: the amount of CO₂ emissions due to evaporative losses of volatile organic compounds. The European emission factor model, ARTEMIS (7), shows that weather parameters affect all these three types of CO₂ emission factors. Hot exhaust emission factor in general decreases with increasing temperature for both patrol and diesel cars and more so for diesel cars. Adverse weather such as precipitation and snow would trigger the use of in-vehicle air conditioning, wiper and window defrost and thus increases the hot exhaust emissions from auxiliary system. Cold start emissions are well-known to be larger in lower temperature conditions, while evaporative emissions increase with the increasing temperature. However, existing studies on the CO₂ emissions from passenger transport usually ignore the influences of weather parameters on emission factors (e.g. 4, 8, 9).

It has also long been known that changes of weather and climate correspond to the changes in travel behaviour (10-12). Various travel behaviour researches examined the role of weather on the changes in travel choices. In terms of mode choice, Sabir (13), Bergström and Magnusson (14), Saneinejad (15) for instance, showed a substantial increase of bicycle trip share in warmer temperature. Liu et al. (16-17) showed that weather effects on mode choice were different in regions with different climates and in trips with different purposes. In terms of destination choice and travel distance, Sabir (13) found that individuals prefer closer destinations for shopping or leisure activities in adverse weather conditions. Böcker (18) showed that a warmer and wetter future climate correspond to an increase in travel distance. In terms of trip frequency, daily trip frequency decreases on windy and snowy days while road traffic flow decreases significantly on rainy days (19-20).

Despite the growing knowledge on the impacts of weather on travel behaviour in general, those knowledge cannot be directly transferred into that on the impacts of weather on CO₂ emissions. On the one hand, changes of weather and climate may lead to a shift in travel behaviour. On the other hand, emission factors of vehicle vary in different weather conditions. Moreover, given that future climate would become warmer and weather would become more
extreme, researchers and policy makers are particularly interested in knowing the change of CO₂ emissions from road passenger transport in such a future climate scenario, compared to the CO₂ emissions under current climate. However, only very few researchers so far analysed the change of CO₂ emissions subject to the change of weather.

Thus, this paper aims to analyse and quantify the amount of CO₂ emissions from road passenger transport due to the change of weather. Using Swedish National Travel Survey, this study first examines which weather conditions correspond to the most/least CO₂ emissions from road passenger transport. Furthermore, several econometric models are estimated in order to derive the marginal effects of weather parameters on the travel behaviour variables, including trip frequency, mode choice, destination choice, travel distance and travel speed for car trips. Those models are then used to derive the amounts of CO₂ emissions given the change of weather and climate. The results provide the changes of amounts of CO₂ emissions in various future climate scenarios compared to the current weather conditions, whereas all the other factors remain unchanged.

The next section describes the details of the datasets and the emission factor models used in this paper. Then, it is followed by presenting the explanatory analysis of CO₂ emissions according to the weather parameters. After that, the econometric models are introduced and the marginal effects of weather variables are presented. Furthermore, the changes of amounts of CO₂ emissions in various future climate scenarios are presented. Finally, this paper concluded by summarizing the findings from the previous sections.

2. THE SWEDISH NATIONAL TRAVEL SURVEY, THE WEATHER DATASETS AND THE EMISSION MODEL

The data used in this paper stem from two data sources. The travel data comes from the 2011 Swedish National Transport Survey (NTS) datasets. The NTS data is a travel diary data where all trips a respondent took in the observed day are recorded, including the trip information as well as individual and household characteristics (21). The data also covers the vehicle information such as the manufactured year of the vehicle and fuel type. The dataset covers whole Sweden from all days of week and from every week of the year. However, one limitation of NTS is that the departure and arrival locations of each trip are only available at municipality level for confidential reason. The weather data comes from the Swedish Meteorological and Hydrological Institute (SMHI). The weather data contains weather information measured every three hours, including temperature, precipitation amounts, visible distance (km), wind speed (km/h), relative humidity, snow depth and air pressure (22).

The weather information were assigned into each trip by matching weather data from the weather station nearest to the centre of departure municipality of that trip and selecting the non-missing value of each weather variable with its measured time closest to the departure time. A detailed description of this approach can be found in 23.

The emission factors were calculated using the European emission factor model, ARTEMIS (7). For private car trips, three types of emissions were calculated, hot exhaust emissions, cold start emissions ($E_c$) and evaporative emissions ($E_e$). Hot exhaust emissions were separated into running hot exhaust emissions ($E_h$) and hot exhaust emissions from
auxiliary system ($E_a$). The corresponding emission factors were calculated accordingly. The total emission of a given trip is then calculated by Eq.(1):

$$E_{\text{total}} = E_h + E_a + E_c + E_e = F_h \times D + F_a \times H + F_c + F_e \times D$$

Where $F_h$, $F_a$, $F_c$ and $F_e$ are corresponding emission factors calculated through ARTEMIS. $D$ denotes the travel distance of the given trip and $H$ denotes the travel time of the given trip in hour. This total emission per trip, $E_{\text{total}}$, is then transformed to the emission per trip per traveller by dividing $E_{\text{total}}$ by the number of individuals accompanied in the given trip. Two assumptions are made for the emission standard of the vehicle and road type. Since the detailed emission standard of the vehicle is not available in NTS but only the manufactured year of the vehicle, it is assumed in this study that vehicles manufactured before 1993 are pre-EU I standard, and those between 1993 and 1996 are EU I standard, those between 1996 and 2000 are EU II standard, those between 2000 and 2005 are EU III standard, and those after 2005 are EU IV or more recent standard (24). Besides, NTS does not provide the travel route for each trip but only the departure and arrival locations (municipalities), it is assumed in this study that trips with urban road conditions are those departure and arrive in the same municipalities and within Stockholm, Gothenburg and Malmö, while trips with rural road conditions are those departure and arrive in the same municipalities but other municipalities than Stockholm, Gothenburg and Malmö. And trips with motorway road conditions are those departure and arrive in different municipalities.

For other transport modes, only the emissions of bus trips are considered. The emission factor of bus is taken as 84 g/km (25). The number of individuals accompanied in a bus trip is taken as the average number of passengers in a bus given the time of the day. The average number of passengers in a bus is taken from alighting/boarding data from four bus lines in Stockholm (26). The value is: 21.25 for morning peak (6:00-9:00), 21.73 for off peak (9:00-15:00), 25.67 for afternoon peak (15:00-18:00), and 17.81 for night time. The CO₂ emissions for trips by walking, cycling, metro/tram, train are taken as 0, while CO₂ emissions for trips made by other modes (flight, boat, etc.) are not considered in this study. Around 8% of total trips in the NTS are made by “other modes”.

3. THE INDIVIDUAL CO₂ EMISSIONS IN SWEDEN

The trip based CO₂ emissions were then aggregated into individual level by summing up CO₂ emissions of all trips made by the given individual. The weighted average of the individual CO₂ emissions was then calculated where the weight is used to represent the whole population in Sweden. On average, 3.73 kg of CO₂ from passenger transport are emitted per individual per day in Sweden, which is slightly less than that from the Dutch study (3.8 kg of CO₂ per person per day) that used Dutch national travel survey in 2005 and much less than that from UK study (4.3 kg of CO₂ per person per day) (8). However, given that study 8 did not consider CO₂ emissions other than running hot exhaust emissions and did not consider weather in emission factors, it is plausible that the difference between individual CO₂ emissions in Sweden and that in Dutch/UK could be even larger.
The individual CO₂ emissions are plotted according to various weather parameters, as shown in Figure 1.

(a) Individual CO₂ emissions (kg/day) in different seasons and regions of Sweden

(b) Individual CO₂ emissions (kg/day) in different precipitation categories
In general, running hot exhaust emissions are the major share of total emissions (around 90%). Cold start emission and hot emission from auxiliary system take part of 10% of total emissions while evaporative emissions are neglectable. From Figure 1, the individual \( \text{CO}_2 \) emissions show clear variations in different seasons and regions. Individual \( \text{CO}_2 \) emissions are larger in summer while lower in winter. Central Sweden has the lowest individual \( \text{CO}_2 \) emissions among three regions, presumably because a larger share of respondents lives in the major, dense, urban areas such as Stockholm and Gothenburg. Previous studies (e.g. 27) have shown that urbanization density is inversely related to GHG emissions. It is worth noting that the individual \( \text{CO}_2 \) emissions are extremely high in the summer of northern Sweden, almost reaching 6 kg per individual per day. This is mainly due to the high vehicle mileage travelled in the summer of northern Sweden, even the emission factor in summer is lower than in winter, as shown in Figure 1(d). However, one should be aware that only 9.3% of total Swedish population reside in northern Sweden. Therefore, its influence on average individual \( \text{CO}_2 \) emissions of whole Sweden is relatively limited. Precipitation and snow conditions seem to be positively correlated with individual \( \text{CO}_2 \) emissions.

### 4. DERIVING THE MARGINAL EFFECTS OF WEATHER ON TRAVEL BEHAVIOUR VARIABLES

The travel behaviour models

The difference in individual \( \text{CO}_2 \) emissions shown in Figure 1 does not necessarily represent the impacts of weather, since other factors may vary significantly in different groups of weather condition classifications. Therefore, estimates that represent the changes in travel behaviour variables solely due to the change of weather are required. Travel behaviour variables, including trip frequency, travel mode choice, destination choice, travel distance and average speed, were well-known to affect the \( \text{CO}_2 \) emissions. Therefore, a series of models were constructed to obtain the marginal effects of weather variables on these five travel behaviour...
variables. Those marginal effects denote the amount of changes in each travel behaviour variable given the change of a weather variable while other factors remain invariant.

Panel mixed binary logit models were used to model the destination choice of non-work trips. The model is simplified as each individual chooses between two destination choices for their non-work trips: the destination is located in the same municipality of departure, or the destination is located outside the municipality of departure. The model has the following general form:

\[
U_{i,j,k} = \alpha_k + X_{i,j} \beta_k + \mu_{i,k} + \epsilon_{i,j,k}
\]

\[
P_{i,j,k} = \int_{-\infty}^{+\infty} \frac{\frac{u_{i,j,k}}{\sum_{k=1}^{2} u_{i,j,k} f(\mu_{i,k})}}{\sum_{k=1}^{2} \sum_{k=1}^{2} u_{i,j,k} f(\mu_{i,k})} d\mu_{i,k}
\]

Where \(U_{i,j,k}\) represents the utility of choosing choice \(k\) (the destination is located in the same municipality of departure, the destination is located outside the municipality of departure) for individual \(i\) and his/her non-work trip \(j\). \(\alpha_k\) is the alternative specific constant, \(X_{i,j}\) represents the explanatory variable set that influences the destination choice, which includes weather variables. \(\beta_k\) represents the corresponding parameters. \(\mu_{i,k}\) is the individual level error term that captures the panel effect, which is assumed to be normally distributed. \(f(\mu_{i,k})\) denotes the probability density function of \(\mu_{i,k}\). \(P_{i,j,k}\) is evaluated through simulation. The panel effect is considered to take into account the fact that several trips were made by the same individual. \(\epsilon_{i,j,k}\) is the iid error term. Two sub-models were estimated for the non-work trips departure at urban area (Stockholm, Gothenburg and Malmö) and at rural area (other municipalities). It is assumed that the destination of the work trip does not change for the given individual given day given the change of weather conditions.

Panel mixed multinomial logit models were used to model travel mode choice. Four sub-models were estimated: work/non-work trips made by individuals with at least one car in household and work/non-work trips made by individuals with no car in household. The choice set was simplified into \{slow mode, bus, tram/metro, others\} for those with no car in household and \{slow mode, car, bus, tram/metro, others\} for those with at least one car in household. Both the car drivers and car passengers were counted as car users.

Panel log-linear models were used to model the trip distance of non-work trips:

\[
\log(D_{i,j}) = \alpha + X_{i,j} \beta + \mu_i + \epsilon_{i,j}
\]

where \(D_{i,j}\) is the trip distance of non-work trip \(j\) made by individual \(i\). \(\alpha\) is the intercept. \(\mu_i\) is the individual level error term and \(\epsilon_{i,j}\) is the iid error term which are assumed to be normally distributed. Three sub-models were estimated for: 1. The non-work trip of which the departure and arrival locations are in urban area and in the same municipality (urban local trips). 2. The non-work trip of which the departure and arrival locations are in rural area and in the same municipality (rural local trips). 3. The non-work trip of which the departure and arrival locations are in different municipalities (long distance trips). It is also assumed that the travel distance for the work trip does not change for the given individual given day given the change of weather conditions.
Panel linear models were used to model the average speed of car trips. Similar as the models for trip distance, three sub-models were estimated for urban local trips, rural local trips and long distance trips.

Finally, the negative binomial model was used to model the number of non-work trips made per individual per day. Again it is also assumed that the number of work trips made by the given individual in a given day would not vary given the change of weather.

A list of explanatory variables used in those models is presented in Table 1. Observed temperature was separated into measures of monthly variation and daily variation, in order to differentiate the impact of variation of “normal”/“as expected” weather conditions between municipalities with the impact of variation of “un-usual”/“unpredictable” weather conditions (17). The “normal” value here is the average monthly temperature during the ten years previous to the analysed year at each municipality where the trip took place. This measure of “normal” temperature represents the local climate of each month in the given municipality. The corresponding coefficients may reveal differences in travel patterns between summer (warmer months) and winter (colder months). The daily variation measure was represented by a Z score, showing the deviation of that value on the given day when the trip took place from its corresponding “normal” temperature. The corresponding coefficients denote the individuals’ behavioural response to an extreme cold/warm day (temperature being much lower than the mean temperature at the municipality in that month). This daily variation measure represented by a Z score was then separated into two intervals: “Z score<0” and “Z score>0”, since both a large positive and a large negative Z scores indicate extreme temperature. An interaction effect between the temperature measures of monthly variation and daily variation was also introduced, as the effects of this daily variation measure may differ in municipalities in warmer or colder months.

<p>| TABLE 1 Explanatory variables used in each model |
|----------------------------------------|-----------------|--------------------|-----------------|--------------------|</p>
<table>
<thead>
<tr>
<th></th>
<th>Destination choice</th>
<th>Mode choice</th>
<th>Trip distance</th>
<th>Average speed for car trips</th>
<th>Number of non-work trips</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Socio-demographics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female (D)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Number of children under 6 years old in the trip (C)</td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Age under 25 (D)</td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Age over 65 (D)</td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Partnered living (D)</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Living type missing (D)</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Low income (D)</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>High income (D)</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Income missing (D)</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Home location in Gothenburg (D)</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Home location in Malmö (D)</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Home location in other municipalities (D)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td><strong>Trip information</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Departure location in Gothenburg (D)</td>
<td>√</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Departure location in Malmö (D)</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td>√</td>
</tr>
</tbody>
</table>
Departure location in other municipalities (D) √ √ √ √
Departure at morning peak (D) √ √ √ √
Departure at afternoon peak (D) √ √ √ √
Departure at night time (D) √ √ √ √
Trip takes place on Monday to Thursday (D) √ √ √ √ √
Trip takes place on Friday (D) √ √ √ √ √
Trip distance (C) √
Square of trip distance (C) √
Vehicle model before 2000 (D) √
Vehicle model 2000-2005 (D) √

Weather condition
Historical monthly mean temperature in the given municipality (C) √ √ √ √ √
Temperature Z score<0 (C) √ √ √ √ √
Temperature Z score>0 (C) √ √ √ √ √
Monthly mean × Z score<0 (C) √ √ √ √ √
Monthly mean × Z score>0 (C) √ √ √ √ √
Precipitation amount (C) √ √ √ √ √
Square of precipitation amount (C) √ √ √ √ √
Snow depth (C) √ √ √ √ √
Snow depth missing (D) √ √ √ √ √

Note: The variables “Living type missing”, “Income missing”, “Snow depth missing” are dummy variables indicating the corresponding measures are missing for the given observation. The purpose of using “missing dummy” instead of pairwise elimination is to keep as many observations as possible for estimation.

C in parenthesis denotes that the corresponding variable is a continuous variable while D in parenthesis denotes that the corresponding variable is a dummy variable.

All the models were estimated through a backward elimination method, where all explanatory variables were initially entered into the model and then those that turn to be insignificant in each step were sequentially removed. The full estimation results of parameters were not shown in the paper due to the limitation of the length of paper. However, the estimated marginal effects of each weather variable were presented in Table 2. As discussed above, those marginal effects represent the changes of a travel behaviour variable given a unit change of a weather variable, while other explanatory variables remain invariant. For instance, as shown in Table 2 (a), one degree increase of monthly mean temperature corresponds to 0.42 percentage increase of the probability of choosing the destination of a non-work trip other than the municipality of departure (a long distance trip).
### TABLE 2 (a) Marginal effects of weather variables in each travel behaviour model

<table>
<thead>
<tr>
<th>Weather variables</th>
<th>Destination choice for non-work trips (Probability of travelling across</th>
<th>Mode choice model (Panel mixed multinomial logit)</th>
<th>Departure in urban area</th>
<th>Departure in rural area</th>
<th>For work and with car</th>
<th>For non-work and with car</th>
<th>For work and no car</th>
<th>For non-work and no car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical monthly mean temperature in the given municipality (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.42</td>
<td>0.23</td>
<td>0.03</td>
<td>-0.01</td>
</tr>
<tr>
<td>(4.91)</td>
<td>(2.68)</td>
<td>(-0.28)</td>
<td>(-0.24)</td>
<td>(-1.67)</td>
<td>(-0.24)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Z score&lt;0 (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
<td>1.41</td>
<td>0.31</td>
</tr>
<tr>
<td>Temperature Z score&gt;0 (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
<td>-1.34</td>
<td>/</td>
</tr>
<tr>
<td>Monthly mean × Z score&lt;0 (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>(-1.04)</td>
</tr>
<tr>
<td>Monthly mean × Z score&gt;0 (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>(2.85)</td>
</tr>
<tr>
<td>Precipitation amount (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>(1.53)</td>
</tr>
<tr>
<td>Snow depth (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Note: '/' means the corresponding variable is eliminated through the backward elimination method. Numbers in parenthesis are corresponding t-values calculated through the delta method (28). Numbers in bold characters are significant at 10% level. Note that it is possible that the given marginal effect is insignificant while the corresponding parameter is significant and kept in the model. For models of destination choice, the marginal effects on the probability of travelling across municipality are presented. For models of model choice, the marginal effects on the probability of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
choosing car are presented for those with car in household. The marginal effects on the probability of choosing bus are presented for those without car in household.
### TABLE 2 (b) Marginal effects of weather variables in each travel behaviour model

<table>
<thead>
<tr>
<th>Weather variables</th>
<th>Trip distance for non-work trips (panel log-linear)</th>
<th>Average speed of car trips (panel linear)</th>
<th>Number of non-work trips per individual per day (Negative binomial)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Urban local trips</td>
<td>Rural local trips</td>
<td>Long distance trips</td>
</tr>
<tr>
<td></td>
<td>Log(D)</td>
<td>Log(D)</td>
<td>Log(D)</td>
</tr>
<tr>
<td>Historical monthly mean temperature in the given municipality (C)</td>
<td>0.007 (2.18)</td>
<td>0.009 (3.59)</td>
<td>0.021 (5.16)</td>
</tr>
<tr>
<td>Temperature Z score&lt;0 (C)</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Temperature Z score&gt;0 (C)</td>
<td>/</td>
<td>0.086 (2.95)</td>
<td>0.129 (2.98)</td>
</tr>
<tr>
<td>Monthly mean × Z score&lt;0 (C)</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Monthly mean × Z score&gt;0 (C)</td>
<td>/</td>
<td>-0.004 (-1.64)</td>
<td>-0.012 (-3.28)</td>
</tr>
<tr>
<td>Precipitation amount (C)</td>
<td>-0.069 (-4.00)</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Square of precipitation amount (C)</td>
<td>0.004 (3.41)</td>
<td>/</td>
<td>-0.001 (-1.85)</td>
</tr>
<tr>
<td>Snow depth (C)</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Model information</td>
<td>Number of observations (trips)</td>
<td>9619</td>
<td>15903</td>
</tr>
<tr>
<td></td>
<td>Number of individuals</td>
<td>3640</td>
<td>5863</td>
</tr>
<tr>
<td></td>
<td>Adjust R square</td>
<td>0.029</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>Standard deviation of individual level error term</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Standard deviation of iid error term</td>
<td>1.03</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Dispersion parameter</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>Log-likelihood</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>AIC</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>
The impacts of weather on the travel behaviour variables

As shown in Table 2, though some travel behaviour variables are relatively invariant to the change of weather, all models exhibit at least one weather variable which has a significant marginal effect. Those marginal effects also indicate the direction of the change of CO₂ emissions, as an increase/decrease of a particular travel behaviour variable has an intuitive interpretation to the direction of change of CO₂ emissions. Besides, the individual level error terms of all models are highly significant even with individual socio-demographic variables being considered. In many models, the magnitude of between-individual variation is even larger than that of iid error terms.

As shown in Table 2, the probability of choosing the destination of a non-work trip outside the municipality of departure would increase in warm months. This indicates an increase of travel distance in warm months, which echoes the finding from Sabir (13). For those departure in rural area, a warmer than normal day indicates a decreasing probability of having the destination outside the municipality of departure. Moreover, this effect tends to be more substantial in cold months. As expected, snow corresponds to a decreasing probability of having the destination outside the municipality of departure, though this effect turns insignificant for those that departure in urban area.

As the use of private car is the major source of CO₂ emissions, Table 2 only presents the marginal effects of weather variables on the probability of choosing car as the main mode in individuals’ work/non-work trips. While for those who do not have a car in household, the marginal effects of weather variables on the probability of choosing bus as the main mode were presented. For those who have at least one car in household, the probability of choosing car for their work trips is relatively invariant to the change of weather, compared to their mode choices of non-work trips, as expected. For their non-work trips, the probability of choosing car tends to increase in a warmer than normal day, especially in cold months, which indicates a substantial increase of CO₂ emissions in that weather condition in winter. Besides, thick snow depth on the ground corresponds to a decreasing probability of choosing car in their non-work trips (16).

For trip distance, a warm month and a warmer than normal day, in general corresponds to a longer trip distance. Precipitation is related to a decreasing trend of trip distance of urban local trips but shows no significant effect on that of rural local trips. Though intuitively precipitation and snow may influence the average speed of car trips, the corresponding variables show no significant effects. However, precipitation and snow influence the destination choice which leads to changes in travel distance and average speed. Besides, monthly mean temperature shows positive effects on the average speed of all types of trips, while the effects of temperature Z score variables and the interaction variables differ in different types of trips. For the trip frequency of non-work trips, only the interaction effect between “monthly mean temperature” and “temperature Z score>0” shows a significant effect.

5、CHANGES OF CO₂ EMISSIONS DUE TO THE CHANGE OF WEATHER

Although the marginal effects of weather variables on travel behaviour variables give intuitive interpretations on the changes of CO₂ emissions due to the change of weather, the overall picture of the effects of weather is still unclear. For instance, from the discussion above, trip distance tends to increase in warm months (an increase in monthly mean temperature). However, the emission factor of car, in general is smaller in warmer months, rising questions on the changes of amount of CO₂ emissions given the change of monthly mean temperature. Therefore, the marginal effects of weather variables on CO₂
emissions were derived based on the travel behaviour models presented in Section 4. Those marginal effects represent the changes of CO2 emissions, expressed in terms of individual CO2 emissions, given a new scenario of weather condition (a new set of values of weather variables).

In order to derive such changes of CO2 emissions, the changes of travel behaviour variables in the new scenario of weather condition were first derived through the travel behaviour models described in Section 4. In general, the derivation of the changes of travel behaviour variables in the new scenario of weather condition is identical to the derivation of the marginal effects of weather variables presented in Table 2, as shown below:

\[
M_w^i = E(Y^i|X_{w, new}^i, \beta) - E(Y^i|X_{w, old}^i, \beta)
\]  

(6)

Where \( M_w^i \) denotes the change of a particular travel behaviour variable for observation \( i \) given a new scenario of weather condition. \( X_{w, new}^i \) denotes the explanatory variable set where the original weather variables are substituted by a new set of weather variables given a particular weather scenario. \( X_{w, old}^i \) denotes the explanatory variable set with the original weather variables. \( \beta \) denotes the estimated parameters of a given model. \( E(Y^i|X_{w}^i, \beta) \) denotes the expected outcome of the travel behaviour variable \( Y^i \), given the explanatory variable set \( X_{w}^i \) and corresponding parameters \( \beta \). For the models of average speed of car trips (panel linear model), the expected outcome: \( E(Y^i|X^i\beta) = X^i\beta \). For the models of trip distance (panel log-normal linear model) and number of non-work trips per day (negative binomial model), the expected outcome: \( E(Y^i|X^i\beta) = e^{X^i\beta} \). For the models of destination choice and mode choice (panel mixed logit models), the change of share of each alternative in the whole sample was first determined. For a given alternative \( k \), the change of number of observations choosing alternative \( k \) due to the change of weather variables is:

\[
N_k = \sum_i P_{i,k}^{w, new} - \sum_i P_{i,k}^{w, old}.
\]  

(7)

Where \( P_{i,k}^{w, new} \) is the predicted probability of choosing alternative \( k \) for observation \( i \) given the new set of weather variables. And \( P_{i,k}^{w, old} \) is the predicted probability of choosing alternative \( k \) for observation \( i \) given the weather variables in the data. The expression of \( P_{i,k}^{w, new} \) and \( P_{i,k}^{w, old} \) is presented in Eq.(3). If \( N_k \) is positive, which means that \( N_k \) observations were shifting from other alternatives to alternative \( k \) due to the change of weather variables, \( N_k \) observations with the highest values of \( P_{i,k}^{w, new} \) among the observations that do not choose alternative \( k \) were selected to shift from other alternatives to alternative \( k \). If \( N_k \) is negative, those with the lowest values of \( P_{i,k}^{w, new} \) among
the observations that choose alternative $k$ were selected to shift from alternative $k$ to other alternatives. Those $N_k$ observations then denote $M^i_w$.

Therefore, the predicted travel behaviour variable given the change of weather is expressed as:

$$Y^i_{new} = Y^i_{old} + M^i_w$$ (8)

Where $Y^i_{new}$ denotes the new travel behaviour variable given the change of weather. $Y^i_{old}$ denotes the travel behaviour variable observed in the data. It is important to note that the predicted travel behaviour variable builds upon the observed data $Y^i_{old}$, rather than the predicted values from the model. The influence of the change of weather variables is expressed in the marginal effect $M^i_w$. The predicted travel behaviour variables according to Eq.(8) were then used to calculate the individual CO$_2$ emissions in the new scenario of weather. A general flowchart of the calculation is shown in Figure 2.

![FIGURE 2 The flowchart of the prediction of CO2 emissions under new weather scenario](image)

As shown in Figure 2, the predicted changes of destination choice given the change of weather were first calculated, in which certain observations shifted from local trips to long distance trips and vice versa given the new weather scenario. Given those changes in destination choices, the changes of average speed profile and trip distance profile were then determined. For those observations which shifted destination choices, $E(Y^i|X^i_{W,new}, \beta)$ of average speed and trip distance were calculated using the function of the new model according to the new destination choice (local trips or long distance trips). The changes in model choice were then determined given the change in trip distance. Those changes in travel behaviour variables and the new emission factors given the new scenario of weather were then used to calculate the CO$_2$ emissions of each trip. The CO$_2$ emissions at trip level were then aggregated into individual level by considering the changes of number of non-work trips per individual per day.

Given the fact that future climate will become warmer and weather will become more extreme and unpredictable, a series of scenarios are considered: 1. The monthly mean temperature increases by 1 °C to 5 °C (a warmer climate). 2. The daily temperature Z score is 10% to 50% more extreme (a more extreme temperature). 3. A combination of scenario 1 and 2 (a warmer climate and a more extreme temperature).
temperature). 4. Precipitation amount is 10% to 50% more (a more extreme rainy conditions). 5. Snow depth is 10% to 50% more (a more extreme snowy conditions).

The predicted change of CO$_2$ emissions in these five scenarios are presented in Table 3.
### TABLE 3 Individual CO₂ emissions in the new scenarios of weather conditions

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Total emissions (g)</th>
<th>Hot exhaust emissions (g)</th>
<th>Hot emissions from auxiliary system (g)</th>
<th>Cold start emissions (g)</th>
<th>Evaporative emissions (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Percentage</td>
<td>Value</td>
<td>Percentage</td>
<td>Value</td>
</tr>
<tr>
<td>Current weather conditions</td>
<td>3733.0</td>
<td>100%</td>
<td>3455.1</td>
<td>100%</td>
<td>144.7</td>
</tr>
<tr>
<td>Monthly mean temperature + 1 °C</td>
<td>3788.7</td>
<td>101.5%</td>
<td>3506.0</td>
<td>101.5%</td>
<td>151.8</td>
</tr>
<tr>
<td>Monthly mean temperature + 2 °C</td>
<td>3849.5</td>
<td>103.1%</td>
<td>3560.7</td>
<td>103.1%</td>
<td>160.2</td>
</tr>
<tr>
<td>Monthly mean temperature + 3 °C</td>
<td>3902.3</td>
<td>104.5%</td>
<td>3605.3</td>
<td>104.3%</td>
<td>170.9</td>
</tr>
<tr>
<td>Monthly mean temperature + 4 °C</td>
<td>3956.1</td>
<td>106.0%</td>
<td>3649.6</td>
<td>105.6%</td>
<td>183.2</td>
</tr>
<tr>
<td>Monthly mean temperature + 5 °C</td>
<td>4015.7</td>
<td>107.6%</td>
<td>3696.9</td>
<td>107.0%</td>
<td>198.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 2</th>
<th>Current weather conditions</th>
<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily temperature Z score + 10%</td>
<td>3752.5</td>
<td>100.5%</td>
<td>3471.4</td>
<td>100%</td>
<td>147.9</td>
<td>102.2%</td>
<td>132.8</td>
<td>99.9%</td>
<td>0.3</td>
</tr>
<tr>
<td>Daily temperature Z score + 20%</td>
<td>3773.8</td>
<td>101.1%</td>
<td>3489.1</td>
<td>101.1%</td>
<td>151.6</td>
<td>104.8%</td>
<td>132.8</td>
<td>99.9%</td>
<td>0.3</td>
</tr>
<tr>
<td>Daily temperature Z score + 30%</td>
<td>3792.1</td>
<td>101.5%</td>
<td>3503.6</td>
<td>101.6%</td>
<td>155.6</td>
<td>107.5%</td>
<td>132.6</td>
<td>99.8%</td>
<td>0.3</td>
</tr>
<tr>
<td>Daily temperature Z score + 40%</td>
<td>3811.4</td>
<td>102.1%</td>
<td>3517.4</td>
<td>102.1%</td>
<td>161.4</td>
<td>111.6%</td>
<td>132.3</td>
<td>99.6%</td>
<td>0.4</td>
</tr>
<tr>
<td>Daily temperature Z score + 50%</td>
<td>3826.3</td>
<td>102.5%</td>
<td>3531.4</td>
<td>102.5%</td>
<td>162.5</td>
<td>112.3%</td>
<td>132.0</td>
<td>99.3%</td>
<td>0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 3</th>
<th>Current weather conditions</th>
<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature + 1 °C and Z score + 10%</td>
<td>3808.1</td>
<td>102.0%</td>
<td>3521.7</td>
<td>101.9%</td>
<td>155.6</td>
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<td>169.2</td>
<td>116.9%</td>
<td>127.9</td>
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<td>Temperature + 3 °C and Z score + 30%</td>
<td>3961.4</td>
<td>106.1%</td>
<td>3649.9</td>
<td>105.6%</td>
<td>185.9</td>
<td>128.5%</td>
<td>125.0</td>
<td>94.1%</td>
<td>0.6</td>
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<tr>
<td>Temperature + 4 °C and Z score + 40%</td>
<td>4052.6</td>
<td>108.6%</td>
<td>3722.9</td>
<td>107.7%</td>
<td>206.9</td>
<td>143.0%</td>
<td>122.2</td>
<td>92.0%</td>
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<tr>
<td>Temperature + 5 °C and Z score + 50%</td>
<td>4139.7</td>
<td>110.9%</td>
<td>3788.7</td>
<td>109.6%</td>
<td>230.9</td>
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<td>120.1</td>
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<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
<th>Value</th>
<th>Percentage</th>
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</thead>
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<td>Precipitation amount + 10%</td>
<td>3731.1</td>
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<td>3453.3</td>
<td>99.9%</td>
<td>144.7</td>
<td>100.0%</td>
<td>135.7</td>
<td>102.1%</td>
<td>0.3</td>
</tr>
<tr>
<td>Precipitation amount + 20%</td>
<td>3732.1</td>
<td>100.0%</td>
<td>3454.2</td>
<td>100.0%</td>
<td>144.8</td>
<td>100.1%</td>
<td>135.7</td>
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<td>100.0%</td>
<td>3455.5</td>
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<td>144.8</td>
<td>100.1%</td>
<td>135.7</td>
<td>102.1%</td>
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<td>Precipitation amount + 40%</td>
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<td>100.0%</td>
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<td>3716.7</td>
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<td>3439.0</td>
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<td>144.5</td>
<td>99.9%</td>
<td>132.8</td>
<td>99.9%</td>
<td>0.3</td>
</tr>
<tr>
<td>Snow depth + 30%</td>
<td>3714.7</td>
<td>99.5%</td>
<td>3437.1</td>
<td>99.5%</td>
<td>144.5</td>
<td>99.9%</td>
<td>132.8</td>
<td>99.9%</td>
<td>0.3</td>
</tr>
<tr>
<td>Snow depth + 40%</td>
<td>3714.3</td>
<td>99.5%</td>
<td>3436.7</td>
<td>99.5%</td>
<td>144.4</td>
<td>99.8%</td>
<td>132.8</td>
<td>99.9%</td>
<td>0.3</td>
</tr>
<tr>
<td>Snow depth + 50%</td>
<td>3713.9</td>
<td>99.5%</td>
<td>3436.4</td>
<td>99.5%</td>
<td>144.4</td>
<td>99.8%</td>
<td>132.8</td>
<td>99.9%</td>
<td>0.3</td>
</tr>
</tbody>
</table>
As shown in Table 3, individual CO₂ emissions tend to increase in the scenario of a warmer climate. Given that the monthly mean temperature increases by 5°C, the corresponding individual CO₂ emissions would increase by 7.6%. Seen from Table 2, an increase of monthly mean temperature corresponds to an increase in trip distance, and therefore increases the likelihood of choosing private car. Although the emission factor of private car decreases with the increase of temperature, this part of reduction of CO₂ emissions does not surpass the CO₂ emissions from the increased use of private car and vehicle kilometres travelled. By looking into different sources of emissions, hot emissions from auxiliary system increase dramatically by 37.0% given 5°C rising of monthly mean temperature, while cold start emissions decrease slightly in a warmer climate, by 9.7%. A more extreme temperature also corresponds to the increase of individual CO₂ emissions, although the magnitude is much smaller than that of the scenario of a warmer climate. Increasing the daily temperature Z score by 50% only leads to 2.5% increase in individual CO₂ emissions. Contrary to the scenario of a warmer climate, cold start CO₂ emissions remain relatively unchanged in a more extreme temperature condition. In the scenario of both a warmer climate and a more extreme temperature, the change of individual CO₂ emission becomes more dramatic. It is worth noting that the change of CO₂ emissions in the scenario of a warmer climate and a more extreme temperature tends to be larger than the sum of changes of CO₂ emissions in each single scenario. For instance, the individual CO₂ emissions increase by 407 g in the scenario of increasing monthly mean temperature by 5°C and increasing daily temperature Z score by 50%, while the sum of the changes of individual CO₂ emissions in each scenario is only 376 g (282.7 g + 93.3 g). It indicates that the CO₂ emissions from passenger transport are likely to increase more than expected in such a joint scenario which is more likely to occur in the future.

In the scenarios of heavier rain situations, the individual CO₂ emissions do not vary substantially. Although the precipitation amount is negatively related to the trip distance of urban local trips, see Table 2, its influence on CO₂ emissions is absorbed by the slightly more preferable usage of car mode in rainy days as well as the increase in emission factors in rainy days, mainly the factor of emissions from auxiliary system. Besides, the individual CO₂ emissions drop slightly in a much thicker snow scenario, although the magnitude is small. It is worth noting that only 30% of all sampled trips are under rainy conditions while only 8% are under snowy conditions. Therefore, changes of precipitation amount and snow depth would only affect the CO₂ emissions of those trips. However, it is plausible that the individual CO₂ emissions may increase/decrease more substantially if the heavy rain and thick snow situations become more frequent, for which this study does not consider.

6. CONCLUSION

Although there is a growing knowledge of the impacts of weather on the change of travel behaviour, the impacts of weather on the CO₂ emissions from passenger transport still receive little attention. However, the impacts of weather on the CO₂ emissions from passenger transport are not directly transferrable from the knowledge of weather impacts on travel behaviour, due to the dual role of weather in travel behaviour change and emission factor change. Therefore, this paper explored the relationship between the changes of weather conditions and the change of CO₂ emissions from passenger transport, by considering the influences of weather on both the travel behaviour and emission factors. This study is a first attempt to get a plausible estimate of the change of individual CO₂ emissions given the change of weather conditions. Using Swedish National Travel Survey Data and weather data from SMHI, the individual CO₂ emissions were calculated by using the emission factors derived from the European emission model,
ARTEMIS model. The individual CO₂ emissions showed clear variations in different seasons and weather conditions. A series of econometric models were used to model the travel behaviour variables that are relevant to individual CO₂ emissions. The marginal effects of each weather variable on those travel behaviour variables were presented. The results in general correspond to the existing knowledge on the impacts of weather on travel behaviour. A warmer climate corresponds to an increasing trip distance thus increases the probability of choosing private car, while precipitation and snow conditions discourage individuals conducting long distance trips.

The marginal effects of weather variables on each travel behaviour variable were then derived and were used to calculate the travel behaviour changes under the new scenario of weather condition. A series of scenarios were considered given that the future climate will become warmer and weather will become more extreme and unpredictable. The scenario analysis showed an increase of individual CO₂ emissions in warmer climate and in more extreme temperature conditions, while increasing intensity of precipitation and snow corresponds to a slightly decrease of individual CO₂ emissions, although it may be due to the fact that only a few trips were sampled in those weather conditions. It is worth noting that the change of CO₂ emissions in the scenario of a warmer climate and a more extreme temperature tends to be larger than the sum of changes of CO₂ emissions in each single scenario.

The results presented in this study indicate the importance of considering weather and climate change in evaluation of CO₂ emissions. Given that most large-scale transport demand-supply interaction models do not consider the impact of weather variability, using the estimated CO₂ emissions from those models as the estimates of future external effects may considerably underestimate the actual future CO₂ emissions. With the global warming and more frequent adverse weather, such underestimation may reach 5% or more. In cost benefit analysis, the underestimated external cost of CO₂ emission would lead to a higher rank for projects with considerable environmental effects. Possible abatement could be to set up a higher marginal external cost for CO₂ emission, higher than the shadow price for CO₂ emission, in order to give a higher weight of CO₂ emission per capital. For traffic management, the efforts then must not only cope with the seasonal and local weather pattern of activity-travel behaviour. For instance, more congestion in a warm summer day is expected. Therefore, appropriate congestion mitigation measurements are needed. Besides, long distance car trips are more preferred in warm months. Freeway management is needed in warm months to cope with the increasing demand.

Nevertheless, one should also be aware of the limitation of this study. First, this study used the National Survey data in which detailed departure and arrival locations are not available. Therefore, detailed land use and accessibility variables were not used in the econometric model. Second, this study derived the marginal effects of weather from econometric models, while some of which showed low model fit. However, a transport model with demand-supply interaction would provide more accurate marginal effects of weather since travel behaviour variable such as average speed is more suitable described in the supply model with detailed speed-density relationship in each link rather than any regression models. Third, the marginal effects of weather variables are likely to vary among regions and countries with different climate (17). A meta-analysis comparing the CO₂ emissions subject to the change of weather would give a comprehensive picture of the influence of weather in a global scale. It was also assumed in this study that the individual activity-travel engagement behaviour would follow the patterns that were exhibited in the NTS. There is no guarantee that the individual activity-travel engagement behaviour would remain the same when the weather characteristics change in the future. All of these issues would be possible future research directions of this study.
REFERENCES

1. Detailed data comparison using vin for uncertainty assessment within the CO₂ monitoring database established under art.8 of regulation (ec) no 443, Institut fur Ökologie und Politik GmbH, 2009


