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ABSTRACT

Despite all mitigation efforts, climate change will impact transport systems. As the exact effects are still uncertain, a range of possible climate change outcomes has to be considered. For that purpose, it is important to have an instrument modeling a transport system and its behavior in different weather conditions. This paper shows that agent-based micro-simulations represent a promising approach for comprehensively modeling the impacts on transport systems. Moreover, based on evidence from previous literature, a new comprehensive classification of the various transport system aspects affected by climate change is proposed: *Transport infrastructure, safety, travel behavior and socio-economic circumstances*. Existing weather-sensitive models are restricted to impacts on *transport infrastructure* and *driving behavior* or include very simplistic *activity-travel behavior* models. Different approaches are sketched for the simulation of regular and unexpected weather conditions within the Multi-Agent Transport Simulation (MATSim). For regular weather conditions, it is proposed to search for tipping points where the performance of the transport system starts to significantly deteriorate due to the weather condition. For certain impacts categories, in particular for *activity-travel behavior,* the degree of impact and sometimes direction varies within the literature, calling for further analysis. Modeling unexpected weather conditions requires the application of the within-day replanning module within MATSim. The key challenge here is the definition of the appropriate replanning strategies when an unexpected event occurs.

INTRODUCTION

There is a general consensus that the transport sector is one of the main contributors to global emissions of greenhouse gases and, thus, one of the key sectors responsible for climate change (*1*). This attracts a great amount of attention from both scientists and the public. Much less debated, and investigated, is the impact of climate change on transport. The issue is not of minor importance, though. On the one hand, despite policies to limit climate change or mitigate its impacts, future changes are irrevocable and some of the climatic effects already visible are irreversible. On the other, transport networks play a crucial role in our society and more frequent adverse and extreme weather events - negatively influencing the performance of transport systems – can produce considerable damage. Hence, the necessity to carefully examine climate change impacts and to develop adaption strategies for the transport sector is the main motivation of this work.

Most of the research currently conducted is focusing on obtaining precise and accurate climate change predictions, but the uncertainty regarding the exact effects is still considerable and impacts will most likely vary regionally. As a consequence, it is impossible to think of adaptation as the reaction to one particular forecast of climate change – with precise characteristics and shape – but rather, as a range of possible measures to counter possible climate change outcomes. In this context, it is of great importance to have an instrument modeling a transport system and its behavior in different weather conditions. From a modeling perspective, however, this is challenging because there is only a limited knowledge on how a transport system as a whole will react to variations in weather conditions. Agent-based micro-simulation is a possible approach to cope with this issue, since it allows to model complex systems based on the behavior of the individual actors involved. This is an easier, although non trivial, task because individual behaviors are easier to observe, comprehend, and model.

Agent-based modeling was not used before to model weather sensitivity of a transport system, but some studies focused on the implementation of weather conditions in micro-simulations. This paper is aimed to explore how weather sensitivity could be added to Multi-Agent Transport Simulation (MATSim) - an existing agent-based traffic simulation - in order to have a tool for the evaluation of climate change impact on the transport sector.

The remainder of this paper is organized in four sections. Section 2 gives an overview of the current scientific knowledge about how climate change and weather in general might influence transport. Existing transport microsimulations aimed to model weather conditions are the topic of section 3. Section 4 proposes an approach to deal with climate change with MATSim and explains what the challenges to be confronted are. Finally, a summary and an outlook are given in section 5.

EFFECTS OF CLIMATE CHANGE ON TRANSPORT

Climate is a measure of the average weather observed over a certain period. According to the International Panel on Climate Change (IPCC), it is usually defined as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years (*2*). Surface variables such as temperature, humidity, atmospheric pressure, wind, precipitation, and atmospheric particle count are used to describe the climate. According to the World Meteorological Organization (WMO), the classical period for averaging these variables is 30 years (*3*). There is a fundamental difference between climate and weather. In contrast to climate, weather denotes the momentary state of these variables and their variations over shorter periods. It basically describes what is happening in the atmosphere at any given time (*3*).

Climate change represents a statistically significant variation in the mean state of the climate or its variability, persisting for an extended period (*2*). Hence, climate change includes changes in the average weather conditions as well as changes in the distribution of the weather around the average conditions (i.e., more or fewer extreme weather events). Since the climate itself entails some variability, it is difficult to make a clear-cut distinction between the inherent climate variability and climate change. The delimitation depends on the considered time frame (*3*).

The impact of climate change on transport is closely related to the influence of weather. In simplified terms, weather varies over time and changes between favorable and adverse conditions. It influences transport at a certain point in time in various ways. The impact is particularly high under adverse weather conditions, which include the following events:

- Rainfall
- Snowfall
- Wind storm
- Fog
- High temperatures / heat wave
- Low temperatures / cold wave
- Flooding

Since the climate represents an aggregate of the weather measured over a certain period of time, climate change affects transport through specific weather conditions, which can be seen as discrete realizations of the climate. In addition, climate change influences transport through its cumulative effect over a certain period of time.

The close relationship between climate and weather suggests that an important part of climate change effects on transport depends on how weather conditions impact transport. Thus, in order to model climate change effects on transport it is necessary to understand and model how weather conditions influence transport. This section deals first with climate change forecast scenarios – that is, what is expected for Europe in the next 50 years. The second part of the literature review highlights how weather conditions influence the performance of the transport system.

Climate Change Forecast

Despite all mitigation efforts, some climate change impacts are unavoidable. For instance, the greenhouse gases already in the atmosphere will affect the climate for at least the next 50 years (*4*). Therefore, it is necessary to develop adaption strategies in order to limit the effects of climate change.

Predicting the future climate is currently a main area of research in environmental science. Numerous studies have been carried out trying to project the future climate (*5-8*). Since the 1980s, enhanced climate models have been developed allowing for a better understanding of the climate and consequently more credible projections. In the latest assessment report, the Intergovernmental Panel on Climate Change projects the following main climate changes for Europe (*2*):

- Northern Europe
  - The warming is likely to be largest in the winter
  - The lowest winter temperatures are likely to increase more than average winter temperatures
  - Mean precipitation is likely to increase
  - Extremes of daily precipitation are very likely to increase
  - An increase in average and extreme wind speeds is relatively likely
- Central Europe
  - The highest summer temperatures are likely to increase more than average summer temperature
  - Mean precipitation is likely to increase in winter but decrease in summer
  - The risk of summer drought is likely to increase
- Southern Europe
  - The warming is likely to be largest in the summer
  - The highest summer temperatures are likely to increase more than average summer temperature
  - Mean precipitation is likely to decrease
  - The annual number of precipitation days is very likely to decrease
  - The risk of summer drought is likely to increase

In addition, it is expected that the duration of the snow season shortens in all of Europe. Snow depth is likely to decrease in most of Europe and thaw depth is projected to increase in most permafrost regions.

The authors of the IPCC Fourth Assessment Report point explicitly to the substantial uncertainties remaining even though many features of the simulated climate change are qualitatively consistent among models and qualitatively well understood in physical terms. For instance, the models disagree on the magnitude and geographical details of precipitation change (*2*). Although the models are coupled with a lot of uncertainty in terms of the magnitude and the detailed regional effects, the main impacts are foreseen consistently.

Based on the work of Koetse and Rietveld (*9*) and Hooper and Chapman (*10*) the following climate change aspects are relevant for transport:

- Increased average temperature
- Increase in the number of hot days
- Decrease in the number of cold days
- Sea level rise
- Increased frequency of adverse weather conditions (e.g. storm or flooding)
- Increased intensity of adverse weather conditions (e.g. storm or flooding)
- More precipitation or drought events
- Seasonal changes (longer summer, shorter winter)

The listed effects will vary regionally and are sometimes ambiguous. Some aspects such as increased average temperature or sea level rise will solely have a cumulative impact on transport over a certain period of time whereas some aspects such as increased intensity of adverse weather conditions impact transport immediately when an adverse weather event occurs.

Weather and Transport

The majority of studies related to weather and transport focus on the impact of adverse and extreme weather events. There is less literature available on the effects of general, less pronounced weather conditions.

A main strand of research examines the impact of adverse weather on speed and capacity for motorized private transport. Results of the work of Ibrahim and Hall indicate that adverse weather conditions lead to a slope reduction of the flow-occupancy function and a downward shift in the speed-flow function (*11*). In addition, the maximum observed flow rates were reduced under adverse weather conditions. Brilon and Ponlet examined the variability of speed-flow relationships on German highways (*12*). Wet conditions clearly reduce the speed and consequently capacity. Kyte et al. found similar results for rural freeways in the United States (*13*). Wet surface as well as snow-covered surface conditions reduced free-flow speed. In addition, they found high winds exceeding 24 km/h to diminish speed, but the variation in this speed drop showed to be high. Low visibility also leads to lower speeds when a critical visibility threshold of 0.28 km was reached. Agarwal et al. observed the greatest reductions in capacities and operating speeds for severe rain, snow, and low visibility (*14*). Nevertheless, the reductions for heavy rain and snow are smaller compared to the values obtained in (*11*) and (*12*). In the Netherlands, Sabir et al. found that snow is the only weather conditions that clearly reduced trip speed (*15*). A speed reduction of 7% in the morning and evening peaks on congested routes was observed. Rainfall showed to have a strong negative effect on trip speed on congested routes, especially during the evening peak. Tsapakis et al. observed that travel times during weekdays in the Greater London area increased under adverse weather conditions depending on the intensity of raining/snowing (*16*). Heavy snow fall lead to the highest increase in travel times. According to their results, lower temperature has only a negligible impact on travel times.

A number of studies report that adverse weather also has an impact on the frequency and severity of accidents (*17*). Chung et al. observed that there were significantly more accidents during rainy days (*18*). Koetse and Rietveld report that the severity of accidents during extreme weather events decreased (*9*).

Some studies point out that adverse weather impacts transport demand. Chung et al. examined the effect of rain on travel demand on a highway in Tokyo (*18*). Results indicate that demand decreases during rainy days. The decrease in daily trips is smaller during weekdays (average of 2.9%) and higher during the weekends (7.9% for Saturday and 5.2% for Sunday). The authors assumed that the higher share of leisure trips on weekends causes the difference in demand decreases. This is confirmed by Cools et al. who highlight that the impacts vary depending on the purpose of the trips (*19*). The authors found leisure trips to be more affected by rainy conditions than commuting trips. Maze et al. mention in their work that transport demand is either postponed, deferred, or eliminated (*17*).

Transport demand is affected by weather in various ways. Khattak and de Palma analyzed results of a behavioral survey in Brussels where commuter's mode, departure time and route selection decisions were examined taking various potential influences into account (*20*). The analysis showed that adverse weather affects commuter's travel patterns. About 50% of the travelers changed their pattern under adverse weather. Departure time was mostly affected, followed by mode and route choice. De Palma and Rochat conducted a similar commuter survey in Geneva (*21*). According to their results, departure time choice is much more affected by adverse weather in comparison to mode and route choice which is in line with (*20*). Interestingly, a lot of commuters do not keep themselves informed on weather. Both studies make no statement about the direction of the impact. Aaheim and Hauge analyzed a survey on travel habits in Norway and confirmed that travel habits depend on weather conditions, but the effects, in particular mode shifts, showed to be small (*22*). Guo et al. found good weather to increase bus and train ridership (*23*). They noticed a decreasing public transport ridership under bad weather conditions such as rain and snow, except for extremely bad weather conditions (e.g. a blizzard) where an increase was observed again. In contrast to the work of (*23*), Sabir et al. report that motorized transportation modes are positively affected when precipitation occurs due to commuters changing from active open-air modes such as biking or walking. Regarding the cancellation of trips due to adverse weather, the work of Madre et al. gives insight (*24*). They studied different travel diary surveys concerning the reported share of persons not leaving their homes on a given reporting day. In some of the surveys considered, people reported that they did not move because of bad weather (*24*). This shows that certain weather conditions can lead to cancellation of trips.

Based on the literature review, we suggest to group the impacts in three categories: *transport infrastructure*, *safety,* and *travel behavior*. *Transport infrastructure* entails all impacts acting directly on the infrastructure. *Safety* impacts relate to the occurrence of accidents and their severity. *Travel behavior* encompasses all effects associated with people’s travel behavior. It can be divided into *activity-travel behavior* and *driving behavior*. *Activity-travel behavior* describes on a higher level how people manage their daily activities and travel. *Driving behavior* includes all effects related to people’s behavior when driving. Table 1 gives an overview of the weather impacts on transport. Impacts on *transport infrastructure, safety*, and *trip-making travel behavior* have been examined more extensively than effects on the *activity-travel behavior*. A literature review on impacts on individual daily travel behaviors can also be found in (*25*).

The magnitudes of the explored impacts vary considerably within the literature. In addition, not only a high variation in the degree of impact, but also in some cases contradictions in the direction of impact can be found. The high variation can to some extent be explained by the different contexts in which the studies have been carried out. The considered region (*14*), traveler’s age (*25*), traveler’s gender (*25*), traveler’s familiarity (*12, 14, 25*), the infrastructure condition (e.g. quality winter maintenance activities) (*14*), the traffic mix (*18, 19*), the differentiation between weekday and weekend (*12*) mediate the impacts and have to be factored in. In particular, the trip purpose plays an important role. Discretionary activities such as leisure are more affected than non-discretionary activities such as working.

TABLE 1 Weather impacts on transport

Effect	Description	Related literature
Category I: Transport infrastructure		
Disruption	-Infrastructure doesn't withstand exposure -Failure of traffic control devices/communication	(*26*)
Infrastructure condition	Reduced adhesion, rolling, and friction coefficients	(*26, 27*)
Number of lanes	Reduced number of lanes	(*26*)
Lifetime	Reduced lifetime	(*28*)
Category II: Safety		
Increased frequency of accidents	Increased frequency of accidents due to adverse weather conditions	(*18, 29*)
Reduced severity of accidents	Decreased severity of accidents due to adverse weather conditions	(*9, 29*)
Category III: Travel behavior		
Subcategory I: Activity-travel behavior		
Departure time choice	Individuals adjust departure time in order to avoid adverse weather conditions	(*20, 21*)
Mode choice	Individuals change transport mode due to adverse weather	(*22, 23, 30*)
Destination choice	Individuals change destination due to adverse weather, e.g. shopping more nearby	(*9, 19*)
Reduction in demand	Cancellation of trips due to adverse weather	(*15, 18, 31*)
Route choice	Individuals adapt their routes due to changing generalized travel costs	(*32-34*)
Subcategory II: Driving behavior		
Free-flow speed	Reduced free-flow speed due to e.g. reduced visibility (snowfall)	(*15, 17*)
Capacity	Reduced capacity of links due to more conservative behavior of agents	(*11, 17*)

Climate Change and Transport

As mentioned above, climate change will impact different aspects of transport. Here we propose a classification of the impacts based on four categories: *Transport infrastructure, Safety, Travel behavior and Socio-economic circumstances*. The classification is based on evidence from previous literature (*9*, *10*), but is rather new and not an adaptation of any previous classification. The categories are introduced hereafter.

Transport infrastructure

Transport infrastructures will have to sustain elevated physical stress levels due to more challenging weather conditions in the future. For instance, buckling of bridges, roadways and rail tracks is expected to occur more frequently due to an increased number of hot days. The amount of rutting on roads is also linked to the number of days with high temperatures (*10*). There are also positive effects. Shorter winter periods will lead to lower winter maintenance costs.

Safety

This class encompasses all effects related to transport safety. As mentioned earlier, a higher frequency of adverse weather conditions is expected for most regions within Europe, which in turn will likely lead to a higher number of accidents. This could also lead to transport safety policy changes in the long run.

Travel behavior

Climate change has an event-specific impact on activity-travel and trip-making behavior when adverse weather conditions occur. In addition, the increased frequency of adverse weather and slowly changing average weather conditions affect travel behavior cumulatively in the long-run. For instance, commuters might switch from motorized modes to non-motorized modes in the long run when the average temperature in a given area increases and fewer precipitation events occur.

Socio-economic circumstances

On a global scale, shifts in traffic flows happen, for example due to shifts in agricultural production or tourism (*9*). These shifts occur slowly and influence transport demand in the long run. Elsasser and Bürki focused on the climate change effects concerning tourism in the Alps in Switzerland (*35*). They found that only regions with transport facilities that can provide access to altitudes greater than 2’000 m (6’557 ft) will be in a good position to deal with climate change (guaranteed snow). This will lead to structural changes in tourism, consequently traffic flows will also change. Leisure trips are mostly affected by this change. For instance, increasing average temperature and a decrease in average rainfall might lead to an increase in leisure trips in some cases.

Table 2 gives an overview of the classification of climate change effects. Within the classes, the impacts can be separated into event-specific and cumulative impacts. Recall that climate change affects transport through specific weather conditions as well as through its cumulative effect over a certain period of time.

TABLE 2 Classification of climate change effects

	Event-specific impacts	Cumulative impacts
Transport infrastructure	-Breakdown -Disturbance -Elevated physical stress levels	-Changing maintenance costs -Changing construction costs -Reduced lifetime
Safety	-Frequency of accidents -Severity of accidents	-Changing transport safety regulations
Travel behavior	-Mode, time, destination, route choice -Reduced free-flow speed	-Changing long-term activity-travel behavior -Driver experience under adverse weather conditions
Socio-economic circumstances		-Structural changes in related sectors (e.g. tourism) -Changes in mitigation policies

It can be seen that climate change effects cannot be equated with weather effects. Not only a fourth category taking socio-economic aspects into account has to be considered, but also cumulative effects in the long-run play an important role when assessing climate change effects on transport.

EXISTING MODELS

Some studies on the impact of adverse weather conditions have been carried out using transport macrosimulations. For instance, Suarez et al. simulated the effects of flooding and climate change in the Boston metropolitan area using Boston's Urban Transportation Modeling System (UTMS) (*36*). Boston's UMTS is a conventional transport simulation that divides traffic generation into four stages: trip generation, trip distribution, modal split, and traffic assignment (*37*). In order to capture flooding effects, they defined different flooding scenarios based on Flood Insurance Rate Maps (FIRMs) produced by the National Flood Insurance Program (NFIP) (*36*). The following assumptions were made:

- The capacity of flooded roads is set to zero
- Flooded residential areas generate no trips
- Commuting trips destined to a flooded area are cancelled
- Shopping trips destined to a flooded area are redirected to the closest commercial area

In this simplified manner, some impacts on *transport infrastructure* and *activity-travel behavior* are taken into account. The UTMS was run with different scenarios and key figures were compared, e.g. the number of cancelled trips. Results showed that in the year 2025 delays and the number of lost trips will almost be doubled in the Boston metropolitan area due to the expected sea level rise and increased frequency of flooding events.

Also, there are a number of transport microsimulations that can take weather impacts on *driving behavior* into account. Zhang et al. assessed the sensitivity of weather-related traffic parameters in the CORridor SIMulation (CORSIM) which is a microscopic traffic simulation tool and allows for studying traffic control and other operational strategies (*26*). They identified the simulation parameters affected by weather events and performed an extended sensitivity analysis in CORSIM in order to find the most sensitive ones (*26*). The authors focused on the following parameters: Car following, lane changing, and free-flow speed parameters on freeways and car following, lane changing, free-flow speed, discharge headway, start-up lost time, and turning speed parameters on arterial streets. Rakha et al. developed a model of weather adjustment factors that can be applied in transport simulations (*38*). The developed model consists of adjustment factors for three key traffic stream parameters: Free-flow speed, speed-at-capacity, and capacity. In order to implement it into microscopic traffic simulations, they used the above described adjustment factors in combination with the modification of certain car-following parameters (*27*). In addition, Rakha et al. adapted adhesion, rolling, and friction coefficients according to the roadway surface condition.

Zhao et al. modeled the impact of inclement weather on freeway traffic speed (*driving behavior*) at macroscopic and microscopic level (*39*). At the macroscopic level, the authors analyzed freeway speed data and corresponding weather data in order to develop a regression model that quantifies the impact of weather conditions on average freeway operating speed. They found speed reduction to be a function of visibility, weather type, precipitation and wind-speed. At the microscopic level, they calibrated the Transportation Analysis and Simulation Systems (TRANSIMS) model to inclement weather conditions (*39*). For calibration purposes, a GPS-equipped vehicle collected vehicle dynamics information (e.g. speed) during normal and adverse weather conditions. The authors observed a higher frequency of acceleration and deceleration maneuvers under adverse weather conditions. Then several model parameters such as maximum de-/acceleration, reaction time, look ahead distance, etc. were adapted based on observed data (*39*).

In summary, it can be said that only few transport simulations are able to take weather impacts into account. And if so, the tools are restricted to modeling impacts on *transport infrastructure* and *driving behavior* or they model impacts on *activity-travel behavior* in a very simplified way. There is a lack of transport simulations that can thoroughly model weather sensitivity of the transport system.

MODEL APPROACH AND CHALLENGES

In this section, possible approaches for modeling weather conditions in transport simulations are discussed. Different implementations are compared for MATSim. In terms of the simulation of vehicles moving in the network, MATSim rather pertains to the group of meso-scale models. It does not allow for a very detailed modeling of individual driving behavior (e.g. lane changing, driver's aggressiveness) as common microsimulations do. Nevertheless, when looking at individual's travel behavior, MATSim can be labeled as a microsimulation since it is able to represent activity-travel behavior on a very fine level of resolution. It is possible to explicitly formulate chained decisions and time-space constraints on individual travel behavior (*40*). This is very attractive for modeling weather conditions since effects on the whole trip chain can be examined. One is able to model complex systems based on the behavior of the individual actors involved. In addition, microsimulations such as MATSim allow for the simulation of large-scale scenarios.

The section is organized as follows: First a short overview of MATSim is given. Then, possible approaches are presented and the main challenges are pointed out.

MATSim

MATSim is an open source, agent-based travel and traffic microsimulation framework and consists of several modules, which can be combined or used stand-alone. Transport demand is derived from daily activity patterns through employing an activity-based demand generation where based on census data and other surveys a sequential list of activities and trips connecting these activities for every person in the study area is produced. In this manner, it is possible to ensure temporal and spatial consistency of travel behavior (*41*). Based on this initial demand, every agent iteratively optimizes its daily activity chain in competition for space-time slots on transportation and activities infrastructure with all other agents through a co-evolutionary approach that consists of the three steps execution, scoring, and replanning.

Every agent has an own portfolio of plans and each day plan includes a daily activity chain and an associated utility value. In the execution step, agents select one daily plan out of their portfolio of plans according to a certain model (e.g., a logit distribution) and execute this plan, i.e. the network loading is performed. In the scoring step, an utility value (so called "score") is assigned to each plan according to its utility function. In the replanning step, a certain share of agents is able to mutate a selected plan, clone a selected plan, or cross a selected plan with another plan. Implemented search space dimensions in MATSim are route, time, mode, and destination choice. If an agent ends up with too many plans, the plan with the lowest score is removed from the agent's portfolio of plans.

Each agent tries to maximize the utility of its daily plan. Through replanning daily plans and eliminating plans with low utility scores an optimization process is employed that corresponds to the principle of the survival of the fittest. The three described steps are repeated until a stochastic user equilibrium is approximated.

Within-day replanning module

In situations where agents are confronted with unexpected events such as accidents blocking a link in the network, the iterative day-to-day replanning approach that is typically applied in MATSim is no longer appropriate. In such a scenario, user equilibrium will not be reached since agents do not have enough information about optimal routes and plans at hand (*42*). In order to simulate scenarios with unexpected events, the framework of MATSim contains a within-day replanning module where agents are able to adapt their scheduled plans during the iteration. In contrast to the iterative day-to-day replanning approach, the within-day replanning approach only simulates one single iteration. Agents cannot use information from previous iterations and have to employ some sort of best-guess strategies (*42*).

In order to allow within-day replanning, the basic process steps of MATSim are adapted. The iterative loop is deactivated, except for situations where a combined approach of within-day and day-to-day replanning is employed (e.g. parking or car sharing). The additional within-day replanning module interacts with the mobility simulation in the execution step (*42*).

Discussion of possible approaches

Since MATSim simulates the activity plans of a certain population for one specific day, the tool is less appropriate for simulating cumulative climate change impacts that have an effect over a period of time. Whereas long-term effects on the travel behavior can be modeled, changes in safety and mitigation policies as well as changing construction and maintenance cost are difficult to implement in MATSim.

From a modeling perspective, the differentiation between regular and unexpected weather conditions is important. In this context, “regular” means that a certain weather condition occurs regularly and travelers are able to adjust their plans because they are confronted with that weather condition more than once. In this case, the iterative approach of MATSim is still valid and can be applied. “Unexpected” weather conditions describe a situation where travelers are confronted with unexpected events such as a debris flow blocking several roads. This type of weather conditions requires the application of the within-day replanning module of MATSim.

In the light of climate change, it is important to examine both types of weather conditions. Unexpected weather events can have severe consequences on the functioning of the transport system and a better understanding of how the transport system (including the micro-level behavior of travelers) reacts to it is crucial. On the other hand, one has to pay attention to impacts of regular weather conditions on the transportation since slowly changing weather patterns might not have such a graspable, immediate impact but can change the performance all the more severe in the long-run.

Simulation of regular weather conditions

The climate change aspects that can be attributed to this category are: Increased average temperature, increase in the number of hot days, decrease in the number of cold days, sea level rise, more precipitation or droughts events, and seasonal changes (longer summer, shorter winter).

Those aspects can be examined with MATSim using the iterative method. We propose an approach where it is analyzed at which point the performance of the transport system starts to significantly deteriorate due to the weather condition. These tipping points can then be compared with climate change projections. If the weather conditions causing the transport system to deteriorate or collapse are expected to occur more often, one is able to get a better picture of the possible effects that climate change entails. This approach has the advantage that thresholds for the considered weather parameters can be determined.

In detail, the approach looks as follows:

The climate change aspect that wants to be examined has to be determined initially. For instance, one might want to study the effects of more precipitation events or the impacts of an increased average temperature. In this context, it is advisable not to limit the analysis to one single weather parameter because in reality the transport system is affected by the joint occurrence of different weather parameters. Therefore, the analysis should include a set of weather parameters that describe a certain weather condition. This facilitates the determination of the direction and magnitude of impacts. Clifton et al. explored the representation of weather in travel behavior models (*43*). Based on the cluster analysis of various daily weather characteristics, they distilled 17 different weather types out of hourly weather data for the region of Sidney. They compared those weather clusters to reported mode shares from the Sidney area household travel survey. The comparison showed that only few weather clusters induce different individual travel patterns. Therefore, the authors stated that the weather types can be further reduced in order to include them into models of trip generation (*43*).

With the weather condition at hand, one can specify the impacts to be studied according to the classification proposed earlier. Previous microsimulation weather implementations focused solely on the *driving behavior* impacts, but a comprehensive tool for assessing *transport infrastructure*, *safety*, *activity-travel behavior*, *driving behavior*, and *socio-economic* impacts is lacking. In the case of regular weather conditions, *activity-travel behavior* is particularly affected. For that purpose, agent-based simulations such as MATSim are very well suited since the behavior of the individual travelers is modeled.

The next step involves the modeling of the impacts. In some cases, this is straightforward. For instance, the impact of precipitation on the *driving behavior* is well studied and therefore easier to model. There is also some work on the variance of road capacities which can be referred to in order to determine the magnitude of impacts on *driving behavior* (*29*). In contrast, adapting the *activity-travel behavior* and modeling *socio-economic* impacts is more difficult because this has not been implemented so far. In addition, slow and moderate changes of the temperature pose a difficulty since the effects are less pronounced.

Regarding the impact on *travel behavior*, the degree of impact and sometimes direction varies within the literature. This calls for further analysis. As mentioned before, it is proposed to analyze the impacts using integrated weather indices taking co-occurrences into account, similar to the work of (*43*). Another important issue for the analysis of travel behavior is to carefully select the location where weather information is chosen from because of the local variation of the weather conditions. In addition, most stations are in rural areas, but high traffic volumes are observed in urban areas (*25*). It is also unclear for which region users obtained the weather information. It could be the origin of the trip, the destination of the trip, or both. Then it is questionable how big the region is for which the user collects weather information. This also depends on trip purpose and distance. The time dimension plays an important role as well because the weather varies significantly over time. Then, one has to take into account that people assess the same weather condition differently. The Swiss Microcensus allows for studying this issue since travelers are asked to assess the weather for the effective day (*44*). This can be compared with actual weather conditions in order to see if the statements in the survey are consistent. Last but not least, one has to consider not only actual weather, but also relative weather. For instance, if the weather is bad on a Saturday, then probably a higher increase of leisure trips on Sunday can be observed even if the weather is not that favorable in absolute terms (*25*).

Transport infrastructure and *safety* impacts can be assessed through a combined approach of within-day and day-to-day replanning. Based on climate change projections and information on how the probabilities of a network disruption or of an accident change, an incident-generator can be implemented in MATSim. This module would then randomly generate incidents on the network and affected travelers would be allowed to do within-day replanning. In order to implement *socio-economic circumstances* impacts in MATSim, the initial demand and supply of the simulation can be adapted according to projected changes of the socio-economic situation.

All in all, it is possible to model the reaction of the whole transport system taking *transport infrastructure*, *safety*, *travel behavior* and *socio-economic circumstances* impacts into account. Additionally, MATSim allows for the simulation of large-scale scenarios which is important for climate change impacts since they take effect on that level.

Simulation of unexpected weather conditions

This category entails the climate change aspects increased frequency and increased intensity of adverse weather conditions. Hooper and Chapman recognized these impacts as being the most devastating aspect of climate change to transportation (*10*). Therefore, the simulation of these effects is of great importance in order to assess the impacts of climate change. Unexpected weather conditions affect primarily *transport infrastructure* and *travel behavior* aspects.

Modeling these conditions requires the application of the within-day replanning module. Similar to the approach for expected weather conditions, the adverse weather condition has to be specified initially. First of all, one has to define the type of adverse weather event to be modeled. Thereupon, the severity of the weather event being modeled needs to be clarified. Then, the spatial and temporal dimensions of the weather event need to be considered and a detailed weather scenario has to be developed. An attractive approach might be to directly use scenarios information stemming from climate change simulations. In MATSim, the *transport infrastructure* impacts can be implemented with a time-variant network where the free-flow speed, capacity, and the number of lanes can be changed at a certain point in time. The key challenge for the simulation of unexpected weather conditions is the definition of the appropriate replanning strategies when an unexpected event occurs in order to model impacts on *travel behavior*. In particular, two aspects have to be clarified. Firstly, it needs to be determined who is allowed to adapt their travel behavior. Depending on the scenario, the selection could be based on time, traveler’s location, and traveler’s individual attributes. Secondly, one has to define what kind of replanning action the identified travelers undertake. Dobler et al. simulated an exceptional event where capacities of several arterial roads in the city center of Zurich, Switzerland, were reduced using the within-day replanning module within the framework of MATSim (*42*). They allowed people passing an affected road to do replanning and implemented a simple behavioral model. The only available replanning action was to change the route. For the simulation of unexpected weather conditions more sophisticated *activity-travel behavior* models are needed where not only the route, but also mode, time, destination choice can be adapted.

SUMMARY AND OUTLOOK

Climate models are getting more and more sophisticated, making more precise and accurate climate change predictions possible, but the uncertainty regarding the exact impacts is still considerably large. Therefore, it is impossible to prepare adaption to one particular forecast of climate change. A range of possible climate change outcomes has to be considered. For that purpose, it is crucial to have an instrument modeling a transport system and its behavior in different weather conditions. Various aspects of the transport system are affected by climate change. Within this paper, a new comprehensive classification of the impacts based on evidence from previous literature is proposed, containing four categories: *Transport infrastructure, safety, travel behavior and socio-economic circumstances*. The category *travel behavior* can be divided into *activity-travel behavior* that describes how people manage their daily activities and travel on a higher level and *driving behavior* related to the realization of a trip on a lower level.

Existing weather-sensitive models are restricted to impacts on *transport infrastructure* and *driving behavior* or they include very simplistic *activity-travel behavior* models. This can be explained by the fact that the majority of studies within this research field focus on impact of adverse weather events on speed, capacity and accident rates in motorized private transport. A tool taking the reaction of the whole transport system into account is lacking. This paper shows that agent-based micro-simulation represent a promising approach for comprehensively modeling the different impacts on the transport system.

Different approaches are sketched for the simulation of regular and unexpected weather conditions within MATSim allowing for the modeling of the reaction of the whole transport system. For regular weather conditions, it is proposed to search for tipping points where the performance of the transport system starts to significantly deteriorate due to the weather condition and compare those with climate change projections. For certain impacts categories, in particular for *activity-travel behavior,* the degree of impact and sometimes direction varies within the literature, calling for further analysis. Modeling unexpected weather conditions requires the application of the within-day replanning module within MATSim. The key challenge here is the definition of the appropriate replanning strategies when an unexpected event occurs.

In a next step, further analysis of regular weather condition impacts should be realized. It is proposed to employ integrated weather indices taking co-occurrences into account. The results should be implemented in MATSim according the proposed approach. Concurrently, it is possible to simulate unexpected events where starting from a very simplified activity-travel behavior model additional replanning strategies should be added in order to enhance the simulation.

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