The Impact of Climate Change and Weather on Transport: An Overview of Empirical Findings

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Abstract

This paper presents a survey of the empirical literature on the effects of climate change and weather conditions on the transport sector. Despite mixed evidence on many issues, several patterns can be observed. On a global scale especially shifts in tourism and agricultural production due to increased temperatures may lead to shifts in passenger and freight transport. The predicted rise in sea levels and the associated increase in frequency and intensity of storm surges and flooding incidences may furthermore be some of the most worrying consequences of climate change, especially for coastal areas. Climate change related shifts in weather patterns may also affect infrastructure disruptions. Clear patterns are that precipitation affects road safety; it increases accident frequency but decreases accident severity. Precipitation also increases congestion, especially during peak hours. Furthermore, an increased frequency of low water levels may considerably increase costs of inland waterway transport. Despite these valuable insights, the net impact of climate change on generalised costs of the various transport modes are uncertain and ambiguous, with a possible exception for inland waterway transport.

Key words: Climate change; Weather; Transport; Overview
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1. Introduction

Climate change is almost invariably considered an issue of global interest. However, the extent to which climate change represents a problem is still a heavily debated issue; calculations on future damages associated with climate change, and therefore also judgments about mitigation and adaptation costs to be made now, differ widely. For example, the influential Stern report claims that 'the benefits of strong, early action considerably outweigh the costs' (see Stern, 2007, p. II). Specifically, assuming no mitigation efforts, the report estimates that climate change may cause a permanent decrease in annual global GDP of between 5% and 20%, thereby claiming justification for large mitigation efforts right now. Although the report has received wide attention, substantial criticism has arisen. For instance, Tol (2006) argues that for 'water, agriculture, health and insurance, the Stern review consistently selects the most pessimistic study in the literature' (see also Lomborg, 2006). Another point of criticism comes from Nordhaus (2006), who focuses on the unusually low social discount rate of 0.1% used in the report. Since a near-zero discount rate gives a large weight to climate change damages in the distant future, GDP losses are large even when distant future damages are small. Using a discount rate that is more generally accepted, Nordhaus shows that the extremely low discount rate used in the Stern report is the main reason for the unusually large damage estimates.

The Stern (2007) and Intergovernmental Panel on Climate Change (IPCC, 2007a) reports analyze damages for, among others, the water, agricultural, health and insurance sectors.[1] A sector that receives fairly little (explicit) attention, however, is the transport sector. This is not entirely surprising, since to date the consequences of climate change and changing weather conditions for the transport sector have not received much attention in the literature. Still, it is widely known that transport systems on the whole perform worse under adverse and extreme weather conditions. This is especially true in densely populated regions, where one single event may lead to a chain of reactions that influence large parts of the transport system. This paper therefore presents an overview of empirical findings on the impact of climate change and weather conditions on the transport sector. It is not exactly meant as a classic literature survey with a full-blown methodological assessment of studies, the topic is too broad for that. Rather we aim to give an overview of empirical insights on various relevant themes and issues. Of course, the main methodological issues are discussed and obvious shortcomings or drawbacks are addressed. The paper reflects a changing orientation in research and policy in the field of climate change. Until recently the overwhelming majority of research outputs in the field was on mitigation, the central issue being the effectiveness and efficiency of measures to reduce the environmental burden of transport (see, for example, Hensher and Button, 2003; IPCC, 2007b).[2] More recently, policy makers have more or less accepted that certain climate changes cannot be prevented, and have therefore started to explore potential adaptation strategies. Of course, adaptation and mitigation strategies are interrelated, i.e., increasing adaptation opportunities imply decreasing urgency to implement mitigation measures, and vice versa.

There are several ways to examine the influence of climate change on transport. One possible route would be to compare transport systems between regions with very different climate conditions, for example by comparing transport in Spain with transport in Norway. Differences in performance of road, rail and waterway transport systems give an indication of the potential impacts of climate change. One of the difficulties of this approach is that differences between countries are the result of a whole range of factors, where in addition to climate also other factors play a role, such as the level of economic development and physical conditions. Another approach to analyze the influence of climate would be to consider seasonal variations in transport and travel behavior. Variations in travel behavior and performance of transport systems between seasons can be partly explained by weather variations. For freight transport, variations in demand will be related to seasonal cycles in some sectors, such as the agricultural sector. For passenger transport one also has to take into account non-weather seasonal effects, such as Christmas holidays and the holiday calendar of schools, which may be partly correlated with weather. A third way to address climate issues would be to consider the instantaneous relationship between weather and travel behavior. This may be expected to lead to clearly visible adjustments, but one should be aware that these are typically short term adjustments.

Most of the contributions in this paper address the short run demand side. Climate and weather may, however, affect the supply side as well (see, e.g., Transportation Research Board, 2008). For example, a supply side adjustment could be that the design of infrastructure is such that it copes with the relevant features of weather conditions, such as performance under extreme weather conditions in terms of high or low temperatures, heavy rainfall, fog, heavy wind, etc. Supply may also be affected at short notice, for example when railway companies and airports stop operations due to extreme wind conditions. Furthermore, most studies on climate and weather concern passenger transport. This makes sense, since behavioral reactions tend to be larger than in freight transport. However, given the nature of transport as a derived demand, trade flow patterns will be affected by climate change in the long run when climate change affects location patterns of production and consumption. In a similar vein seasonal variations may occur. Further, freight transport will be affected when climate or weather changes lead to changes in generalised costs of transport, directly or indirectly. For example, extreme weather may lead to accidents on roads, implying delays for both passenger and freight transport.

The remainder of this paper is organized as follows. First we discuss the change in climate and weather conditions that likely are most important for the transport sector in Section 2. In Section 3 we discuss consequences for transport demand on a global scale related to changes in tourism and agricultural production. Section 4 focuses on sea level rise, storm surge and flooding and their effects on especially transport and transport infrastructure in coastal areas around the globe. We then turn to the effects of weather and climate change on infrastructure disruptions. Section 5 addresses the inland navigation sector, Section 6 discusses the existing insights for rail and air transport, and in Section 7 we address road transport. In Section 8 we discuss the behavioral responses to changes in weather and relative costs of transport modes in passenger and freight transport. Section 9 concludes.[3]

2. Climate change

With respect to (the consequences of) climate change many uncertainties exist and the existing climate models can be criticized on a number of points. Still, these models are the current state-of-the-art, and to our knowledge there are few systematic analyses that point to climate developments that are opposed or substantially different from the ones predicted by the bulk of the models. Although some extreme contrary climate change scenarios exist, they are not likely and they too are surrounded with large uncertainties. In this section and throughout this paper we therefore assume that the general direction of climate change as predicted by most climate models across the globe is correct. Note that we do not in any way state or come to the conclusion that climate changes as they are reported in contemporaneous climate change reports, such as the IPCC (2007c) report, are correct.

The main consequences of climate change as predicted by most of the existing climate models are an increase in global temperatures, changes in precipitation patterns, and sea level rise. In general, climate models predict that increases in temperature will be higher over land areas than over oceans and seas, higher in interiors of continents than in coastal areas, and higher when going from the tropics to the polar region in the Northern Hemisphere (IPCC, 2007c). The potential consequences of climate change for precipitation patterns are more complex, and depend largely on continental geometry (vicinity of water) but also on the vicinity and shape of mountains and on wind flow direction. In general the existing climate models predict that precipitation will increase in areas adjacent to the Polar Regions, and will decrease in areas adjacent to the tropics. Furthermore, tropical precipitation is expected to increase especially during the rainy seasons. Global sea level rise in 2100 for the six SRES (Special Report on Emissions Scenarios) marker scenarios ranges between 0.18 and 0.59 meter above 1990 levels (IPCC, 2007c).[4] The six SRES marker scenarios do not include additional measures for mitigation of greenhouse gas emissions, e.g., Kyoto measures are not incorporated. Also these estimates do not include further acceleration in the melting of the Greenland and West Atlantic ice shelves. Given these changes, Table 1 lists the effects on climate and weather conditions that are probably most relevant for the transport sector along with the likelihood of their occurrence.

Observe that the consequences for global temperatures and sea level rise are almost certain or very likely. Uncertainty is largest with the respect to the consequences for precipitation patterns and wind strengths, storms and hurricanes. Furthermore, the effects in the table are qualitative in nature; the level of uncertainty surrounding climate change increases substantially when quantitative effects are considered. Moreover, climate changes and the degrees to which they will occur are different for different regions. In Appendix A we list the relevant effects of climate change for different regions across the globe. Given these differences in climate change it is obvious that impacts of climate change on the transport sector will also differ across regions. It should furthermore be noted that, due to differences across regions in the vertical movement of land and coastal erosion, local sea level rise can be quite different at different locations, with obvious consequences for changes in flooding probabilities.

Table 1. Likelihood of changes in climate and weather most relevant for (US) transport

Change in climate or weather	Likelihood
Decreases in very cold days	Virtually certain
Increases in Arctic temperatures	Virtually certain
Later onset of seasonal freeze and earlier onset of seasonal thaw	Virtually certain
Increases in very hot days and heat waves	Very likely
Sea level rise	Virtually certain
Increase in intense precipitation events	Very likely
Increases in drought conditions for some regions	Likely
Changes in seasonal precipitation and flooding patterns	Likely
Increases in hurricane intensity	Likely
Increased intensity of cold-season storms, with increases in winds and in waves and storm surges	Likely

Source: Transportation Research Board (2008), Table 2-1

3. Extreme events: Sea level rise, storm surge and flooding

Sea level rise and the associated increase in frequency and intensity of storm surges and flooding incidences are perhaps among the most worrying consequences of climate change, especially for coastal areas. With respect to North America the IPCC (2007a) report states that coastal flooding due to sea level rise and storm surge is one of the most serious effects of climate change, especially along the Gulf and Atlantic coasts (see Field et al., 2007). Some studies even predict that transport infrastructure in some coastal areas along the Gulf of Mexico and the Atlantic will be permanently inundated some-time in the next century (see, e.g., Gornitz, 2001; Dingerson, 2005). Below we discuss the extent to which transport infrastructure is affected by future sea level rise and flooding, after which we turn to an assessment of damages of flooding incidences.

3.1 Transport infrastructure affected by sea level rise and flooding

It is clear that sea level rise, storm surges and flooding incidences will become increasingly relevant for various coastal regions around the globe. Studies that analyze the impact of sea level rise on the transport system generally (if not all) analyze use of land elevation data Geographical Information Systems and show that the effects are likely substantial. For example, many elements of the transportation system in the US Metropolitan East Coast region lie at 2-6 meter above the current sea level, which is well within the range of future storm surge predictions assuming a global sea level rise of 1 meter (Jacob et al., 2001). In a more recent study Jacob et al. (2007) estimate that a 1 meter global sea level rise would increase the frequency of coastal storm surges and flooding incidences by a factor 2 to 10, with an average of 3. They show that especially the lowest critical elevations of important infrastructure elements in the New York metropolitan area are at risk of being flooded more often and more intensely.[5]

In ICF (2008) the impact of sea level rise on various types of transportation infrastructure along the East Coast of the United States is analyzed. Using digital elevation models they identify "transportation infrastructure that, without protection, will regularly be inundated by the ocean or at-risk of periodic inundation due to storm surge …" (ICF, 2008, p. 6). Estimates are made for the years 2025, 2050, 2075 and 2100 using low and high estimates of global sea level rise from the SRES scenarios.[6] For reasons of space we only discuss results of a sea level rise of 59 cm in 2100 (see Table 2). Although only small parts of roads and railroads are affected by regular inundation, this may still lead to large impacts due to network effects. The parts of the road and rail network that are at-risk are more substantial especially in Washington D.C. Apart from Virginia, the areas of airport property and runways affected are relatively small. The port areas affected are substantial, however, except for Washington D.C. With the total area affected between 25% and 37%, future operational problems are likely severe in Maryland, Virginia and North Carolina if no adaptation measures are taken.

Table 2. Percentage of transportation at-risk and impacted by regular inundation through storm surge in four US states, assuming a sea level rise of 59 cm in 2100 [a]

	Washington D.C.		Maryland		Virginia		North Carolina	
	RI [b]	AR [c]	RI	AR	RI	AR	RI	AR
Length								
Interstates	0%	5%	0%	0%	0%	1%	0%	0%
Principal Arterials	0%	4%	0%	1%	0%	1%	1%	1%
NHS Minor Arterials	0%	0%	1%	4%	0%	0%	2%	2%
National Highway System	0%	5%	0%	1%	0%	1%	2%	2%
Rails	0%	5%	0%	1%	0%	1%	0%	1%
Area								
Ports	0%	0%	20%	12%	11%	24%	12%	35%
Airport Property	0%	0%	1%	1%	2%	3%	1%	2%
Airport Runways	0%	0%	0%	0%	2%	3%	0%	2%

[a] In the table zero percent does not mean that there is no effect; this is only due to rounding. Furthermore, regularly inundated areas and areas at-risk are mutually exclusive.

[b] Regular Inundation

[c] At Risk

Source: Data taken from ICF (2008)

Similar exercises are performed for the Gulf Coast region in the USA (see Kafalenos and Leonard, 2008). Using scenarios of 61 cm and 122 cm relative sea level rise they find that the former has the potential to affect 64 percent of the region's port facilities, while a 122 cm rise may affect as much as three-quarters of the region's port facilities. Although the figures for highways and rails are considerably lower, they are still substantial. Moreover, as stated previously, even when small portions of the network are affected this may lead to large disruptions at the network level. Given the predicted increase in intensity and number of hurricanes under climate change in 2100 the study also analyzes the vulnerability of the region to storm surges. They find that around 50% to 60% of the roads, 30% to 40% of the railway lines, and 22 to 29 of the airports are vulnerable to surges of 5.5 to 7 meters. Moreover, approximately 98% of the ports are vulnerable to surges of this magnitude. Although no damage estimates are given, the potential disruptions and associated welfare loss are clearly substantial. The vulnerability to sea level rise of especially port cities is confirmed by OECD research. Assuming a .5 meter global sea level rise for the year 2070, and taking into account city-specific extreme water levels and natural subsidence or uplift, Nicholls et al. (2008) analyze the changes in exposure to flooding for 136 large port cities around the globe. Substantial increases for 2070 are found in terms of population and asset value exposed, both for develop and developing countries. Although no direct evidence is provided for the impact of sea level rise on the disruption of port activities, it is clear that freight transport and freight transport patterns by sea may be affected to a substantial extent. As also stated by the authors, this warrants more detailed and more local research into sea level rise impacts.

Shifting our attention more specifically to developing countries, Dasgupta et al. (2007) use data from various sources to analyze the impact of 1 to 5 meter sea level rise on 84 developing countries around the globe. Although they do not explicitly assess the impact on transport and transport infrastructure, they do analyze the amount of urban area affected. This likely gives a reasonable impression of the impact of sea level rise on transport infrastructure.[7] The average amount of urban area affected for the 84 countries is 1.02% for a 1 meter sea level rise (4.68% for a 5 meter sea level rise). More interesting are the differences between the 5 regions that are distinguished in the study. High impact regions are Middle East and North Africa (1.94%) and East Asia (1.71%), and low impact regions are Latin America and the Caribbean (0.61%), Sub-Saharan Africa (0.39%) and South Asia (0.33%). Disparities between specific countries are even larger, the effects being especially large in Vietnam and

Guyana (around 10%), French Guiana and Mauritania (around 8%), and Egypt, Libya, United Arab Emirates, Tunisia, Suriname and The Bahamas (4-6%).

The costs associated with infrastructure damages by future sea level rise, storm surge and flooding can be substantial. Moreover, extreme cases such as hurricanes Katrina and Rita may become frequent and may have even larger impacts in the future because of an increased sea level. In these two cases cost estimates are large. Grenzeback and Lukmann (2007) show that the readily available and reported total costs related to infrastructure damages caused by Katrina and Rita amount to around 1.1 billion US Dollar, while a full assessment of damages to rail lines, pipelines, ports, waterways and airports will probably add billions of US Dollars more. Moreover, this study focuses on freight transport and on national and regional transport facilities only, thereby likely underestimating the total costs by a substantial margin. In a broad study by Jacob et al. (2007), assuming a 1 meter global sea level rise, the annualized costs of infrastructure damages due to flooding incidences for the Metropolitan East Coast in the US are estimated to increase by a factor 3. This implies that costs will increase from approximately .5 billion US Dollar per year in 2000 to 1.5 billion US Dollar per year in 2100. This is not taken into account possible changes in hurricane frequency and intensity, which may lead to a more frequent occurrence of extreme cases such as Katrina and Rita, with associated extremes in costs of infrastructure damages and mobility effects.

3.2 Network and mobility effects

Next to the costs of flooding that are related to infrastructure damages, indirect costs due to network effects, i.e., costs due to delays, detours and trip cancellation, may also be substantial. Although there is little empirical evidence on this subject, some exceptions exist. In a study by Centre of Transport and Navigation (2006) in the Netherlands the economic costs associated with changes in traffic and transport due to a single flooding incident in The Netherlands are estimated. The study analyzes mobility effects based on predictions of a transport network model and is meant as a quick scan in order to assess the order of magnitude of the effects. For instance, transport effects of evacuations and calamity tourism are not taken into account. The study distinguishes between four transport scenarios, which vary with respect to the length of the period after the flooding incident and with respect to assumptions on certain behavioral assumptions and effects. To arrive at the economic costs associated with these scenarios, different values of time (in 2010 Euro) are used for different trip purposes and extra costs per kilometer (gas, etc.) are calculated. The costs vary from € 414 million to € 1.1 billion depending on the scenario.

Suarez et al. (2005) also focus on the indirect costs of flooding due to mobility effects. They investigate the impact of climate change on urban transportation in the Boston Metropolitan Area. The area is interesting because it is situated along the coast and has numerous river systems. In the study the effects of coastal flooding due to sea level rise, and of riverine flooding due to heavy rainfall events, on the performance of the urban transportation system are simulated using the Urban Transportation Modelling System (UTMS). Effects are expressed in terms of cancellations of trips and in terms of delays due to rerouting and changes in congestion. Assuming a sea level rise of 0.3 cm per year, and an increase in the magnitude of heavy rainfall events of 0.31% per year, the results show an increase in delays and lost trips of around 80% in 2100 compared to 2000. Using relatively high values of time the associated discounted costs are less than 100 million US Dollar, leading the authors to argue that the effects are too insubstantial to warrant large adaptations to infrastructure. On the other hand, they also note that applying the model to cities that have more low-lying areas, such as Tampa, Cincinnati, and especially New Orleans, may produce more dramatic results. Furthermore, the study does not include costs of infrastructure damages, which are likely substantial. Moreover, a sea level rise of 30 cm in 2100 may underestimate actual developments.

The Suarez et al. (2005) study also shows that increased risk of a flooding incidence may not only be relevant for coastal regions. Given the projected increases in heavy rainfall events, incidents such as the flood-producing rainstorms in the Chicago metropolitan area in 1996 may occur more frequently. This particular flood led to substantial damages to and travel delays on highways and railroads. Moreover, around 46,000 commuters were unable to reach Chicago for up to three days, more than 300 freight trains were delayed or rerouted, and multiple bridges collapsed or had to be replaced. The associated costs were estimated at 48 million US Dollar (see Changnon, 1999).

Clearly the network effects of extreme events such as a flooding incidence may be substantial. Ex-ante information on which parts of the network are most vulnerable to flooding, and which parts are most critical in terms of mobility effects and accessibility of crucial facilities such as hospitals, is essential for decision making on potential adaptation strategies. There is a growing body of research in this area. In these studies network models are generally used for issues such as the identification of critical points in an infrastructure network and analyzing the consequences of capacity restrictions and failure at specific network nodes (see, for example, some of the contributions in Murray and Grubesic, 2007 and Gorman, 2005). Ultimately, combining such network models with specific insights on climate change, much like the studies discussed earlier in this section, may give a clear picture on the most vulnerable and crucial parts of the available transport infrastructure in a specific area. Design of possible adaptation strategies, such as improving flood-defenses or increasing infrastructure resilience at crucial points, may go from there.

3.3 Discussion

Although predictions of sea level rise differ widely, it is clear that even for moderate levels substantial transport damages may arise in many coastal areas around the globe. These damages not only consist of damages to infrastructure, also costs related network effects (travel delay and rerouting) may be substantial. In general, the studies that have been done in this area estimate the direct effects of sea level rise and the indirect effects of sea level rise through storm surges on flooding incidences. Effects of climate change on the frequency and intensity of storm surges are left out of the equation. Given the damages related to Hurricanes such as Rita and Katrina, additional research on this particular issue is necessary. Also, most studies are done for the US East Coast; insights for the US West Coast and Europe are largely missing. Finally, a rather substantial drawback of all studies considered in this section is that they are done for aggregated areas only and that flood defenses that are already in place are not included in the analyses. Although current defenses in most developing countries are limited in scale and scope, defenses in developing countries, and especially those in Europe, are generally well-developed. Therefore, the insights provided here may have limited value for assessing future flood-risk and exposure for specific locations (and likely also overestimate total exposure and damages due to climate change). They may, however, give a good approximation of future exposure to and damages from flooding incidences when flood defenses fail.

4. Climate change impact on global transport patterns

4.1 Passenger transport: Patterns in tourism

Climate change may have several consequences for transport demand on a global and regional scale. The potential changes in patterns of tourism are of special interest. Especially the predicted increases in temperature could have substantial effects on tourism and the associated patterns in passenger transport. Nicholls and Amelung (2008) investigate to what extent the increase in temperature influences the touristic attractiveness of countries in Europe. Their analysis shows that during the summer months Northern parts of Europe become more attractive, while Southern parts become less attractive. Moreover, the length of the holiday season in Northern countries increases. We may therefore expect a decrease in tourism from North to South, and, especially during the summer months, an increase in tourism from South to North. However, during spring and winter the Southern countries become more attractive, which may increase tourism to this region in these periods (see also Amelung and Viner, 2006). Hamilton et al. (2005) make use of data on arrivals and departures of tourists from 207 countries. They model the impact of climate change on tourism and also find a shift from Southern to Northern countries (see Bigano et al. ,2006, for a similar analysis and results). Next to the associated changes in transport patterns they also find a slight decrease in tourism related vehicle kilometers. The underlying reason is that people from the area that produces most of the tourism kilometers (North-Western Europe) stay closer to home.[8]

Next to tourism during the summer holidays, another substantial part of the tourism industry is related to skiing holidays. The impact of climate change in this respect is clear; the larger the increase in temperature, the smaller the probability of sufficient snow for skiing purposes. This may lead to a decrease in skiing holidays and to a shift towards those areas with higher probabilities of sufficient snow, e.g., areas at higher altitudes. Elsasser and Bürki (2002) analyze the effects of climate change on the Swiss tourist industry, and show that the snow certainty of skiing areas in Switzerland decreases from 85% to 44% (see Harrison et al., 1999, for an analysis of Scotland). A study by Scott et al. (2001) uses extensive simulations to model the impact of climate change on the length of the skiing season in a popular skiing area in Canada. Assuming the current state of technology with respect to making artificial snow they calculate that the season will be 3-17% shorter by 2020, 16-52% shorter by 2050 and 30-66% shorter by 2080. Also striking are the differences in vulnerability between the different skiing areas. In that respect it is difficult to judge to what extent climate change leads to a decrease in skiing related tourism, especially when taking into account the increasing technological potential for making artificial snow. Also uncertain is the extent to which climate change leads to a shift to skiing areas at higher altitudes. Another theme that has received little attention so far is the potential shift from skiing holidays to other types of holidays during winter or summer when the availability of snow during winter months actually becomes a problem.

4.2 Freight transport: Shifts in agricultural production

Regarding the production of goods and services the sector that will probably be affected most is the agricultural sector. On a global scale especially the increase in temperature may have a substantial impact on patterns in production and the associated patterns in trade and freight transport. Results from a broad based research project into the effects of climate change on food production on a global scale show that especially countries at higher longitudes will become more suited for food production (see Easterling et al., 2007). The climate in countries at lower longitudes, among which the largest part of developing countries, will become substantially less suited, however. This likely results in an increase in freight flows from developed to developing countries (see also Fischer et al., 1994, 2002). It is difficult to quantify the effects, however, largely because of uncertainty in the extent of climate change, both globally and regionally, uncertainty in adaptation potential and technological change, and uncertainty regarding socio-economic developments. The shift of food production from south to north will likely also hold at the regional level, e.g., from South- to North-Europe and from South-America to

North-America. On this level, however, uncertainty on the consequences for transport patterns and demand are even larger than on a global scale.

In other economic sectors the effects of climate change will generally be smaller than in the agricultural sector, although certain patterns are clear. In moderate climate zones the demand for energy during the winter months will decline. This may, for example, lead to a decrease in demand for oil and coal in electricity production, having implications for transport of fuels. In zones with higher temperatures, on the other hand, demand for electricity for cooling will increase during summer months.

5. Inland shipping: Economic loss due to low water levels

An obvious consequence of increasing temperatures is reduced ice cover on rivers and lakes in various regions across the globe, e.g., Great Lakes in Canada, rivers in Russia. Although it is recognized that this opens up possibilities for increased transport by water, few studies actually assess this potential. For instance, Lofgren et al. (2000) show that a positive effect of climate change may be a substantial reduction in ice cover on the Great Lakes in Canada, but they do not assess the (potential) positive consequences for the commercial shipping sector (see also Permanent International Association for Navigation Congresses, 2008). Another consequence of increasing temperatures is the clearing of ice at and around the North Pole. This may open up the possibility for sea transport on the Northwest Passage during at least several months per year. This route may provide opportunities for more efficient transport between North-America, Europe and Russia and Asia. Some of the existing insights on this subject are pessimistic about the future potential for transport along this route. According to Birchall (2006), those who predict an ice-reduced or ice-free Northwest Passage tend to oversimplify the nature of the ice regimes in the archipelago, thus exaggerating the potential for increased shipping (see also Griffiths, 2004). A more positive assessment can be found in a recent study by Somanathan et al. (2007). They use simulations to analyze the economic potential of the Northwest Passage for transport from St. John’s Newfoundland to Yokohama assuming year round shipping potential. They show the passage is preferable to other routes even when incremental capital investment in ships is high. Extending the route to New York would, however, make the passage unprofitable in their model. Although the potential to use the Northwest passage appears promising for some transport routes, the study also shows that economic feasibility of the passage depends on many uncertain cost factors. Moreover, it is uncertain whether year round usage of the passage will be possible in the future.[9]

Changes in temperature and precipitation also have consequences for water levels in rivers and thereby for the inland shipping sector. Specifically, low water levels in rivers may disrupt transport by water in river basins such as the Mississippi and the Rhine where many goods (bulk freight) are transported by barges. Low water levels will force inland waterway vessels to use only part of their maximum capacity, which may considerably increase transportation costs.[10] Not much research has been done in this area. In an early study Marchand et al. (1988) use a hydrologic model to predict changes in water levels and water level variation due to climate change for the year 2035. By applying an extensive transport model they subsequently simulate the consequences of these changes for average annual shipping costs in the Great Lakes – St. Lawrence river system in Canada. They show that mean annual shipping costs from 1979 to 2035 may increase by 5% because of low water levels. Moreover, they find a large increase in the frequency of extreme costs. Results from this 1988 study may be criticized because climate change scenarios around that time were not as advanced as they are now. In a recent study on the consequences of climate change for shipping in the Great Lakes river system, Millerd (2005) estimates that increases in average operating costs may indeed be substantially higher. Specifically, using climate change scenarios for 2030 and 2050 from the Canadian Centre for Climate Modelling and Analysis, he estimates that compared to 2001 the average operating costs in 2030 increase by 3% to 14% depending on the industrial sector, with an average of approximately 8%. Estimates for 2050 range from 6% to 22%, with an average of 13%.[11]

Results of a similar exercise for the Middle Mississippi River are reported in Olsen et al. (2005). They estimate losses in shipper savings, defined as the difference between costs of shipping and costs of the cheapest transport alternative, due to low water levels for the period 1933 to 2002. Losses over the entire period amount to 77 million US Dollar per year on average. Because of wetter weather conditions the annual losses in the 1968 to 2002 period were substantially lower (25 million US Dollar per year). Subsequently they simulate the impact of climate change using synthetic water flows for 2100 from three GCM climate change scenarios. Since these scenarios produce very different estimates for future precipitation patterns and run-off, the results vary widely. In the first scenario the costs increase from 77 to 118 million US Dollar per year, while in scenarios 2 and 3 the costs decrease to 10 and 24 million US Dollar per year, respectively.[12] The models furthermore differ with respect to the costs of high water levels, which may lead to temporary closure of the river system for freight transport. The pattern in the results is exactly opposite the pattern found for low water levels. Costs for the 1933 to 2002 period amounted to 12 million US Dollar per year. Costs for the first climate change scenario decrease to 1.5 million US Dollar per year, while costs increase in scenarios 2 and 3 to 27 and 41 million US Dollar per year, respectively.[13]

Shifting our attention to Europe, Jonkeren et al. (2007) analyze freight prices of approximately 2,800 shipping trips on the river Rhine in the period January 2003 to June 2005. Approximately 70% of inland shipping in the EU is transported on the Rhine. Water levels are measured at Kaub, which at low water levels is the bottleneck for a substantial part of the Rhine market.[14] Further, since water levels have no effect on freight prices arranged through long-term contracts, only transport enterprises that operate on the spot market are included in the dataset. Applying regression analysis to explain on the spot freight prices per ton transported, the study clearly shows increasing freight prices at decreasing water levels. It is estimated that in the period 1986-2004 there has been an annual average welfare loss of € 28 million due to low water levels in the river Rhine. The estimated loss in 2003 was as high as € 91 million due to the very dry summer in that year. Although these results are based on historical data they have clear consequences for the inland shipping sector under climate change. Climate change scenarios for Western Europe show that the incidence of low water levels will increase, making inland shipping less attractive relative to road or rail transport, ceteris paribus, potentially causing a modal shift from water transport to rail and road transport.

6. Rail and air transport

6.1 Rail transport: Infrastructure failure and accidents

Studies that investigate the effects of weather or climate change on rail transport and infrastructure are scarce. In Duinmeijer and Bouwknegt (2004) the frequency and distribution of rail infrastructure failures due to adverse weather conditions in the Netherlands in 2003 are reported. Weather appears to cause approximately 5% of all rail infrastructure failures (i.e., 5% of 8,279 failures in The Netherlands in 2003), which is limited but far from negligible. Most of the weather-related failures are caused by high temperatures, icing, storm and lightning. However, within the reporting system of Prorail it is assumed that when, for instance, temperature is between certain values it cannot cause a failure. When this assumption would be removed, and therefore failures would be reported differently, the number of failures attributable to adverse weather conditions would likely double to around 10% (personal communication). A study by Rossetti (2002) shows that for 66 out of 5,700 accidents and incidents in the US between 1993 and 2002 the reported primary cause was weather, a figure much lower than that for The Netherlands. Alternatively, when looking at the weather conditions at the time of the accident, snow, fog and rain seem to account for 131, 81 and 411 accidents, respectively. This would amount to approximately 10% of all failures, which would be more in accordance with the Dutch situation. The main causes of weather-related problems in both countries are, however, very different. Clearly, more detailed research is needed in this area. In general, climate change likely causes an increase in heat-related disruptions but a decrease in ice-related disruptions, making the net impact ambiguous and region-specific.

6.2 Air transport: Delays, cancellations and accidents

For the aviation sector wind speeds are important because of their impacts on safety. Extreme wind speeds imply that aircrafts are not allowed to land at the designated airport and have to land at alternative airports. This has large cost implications, both for the airlines and the travelers. In a similar vein, high winds imply that the departure of aircrafts will be delayed. Wind speeds and their directions also have implications on the use of runways. Strong cross winds have an impact on the probability of accidents. For example, one of the larger aviation accidents at Schiphol airport was due to a landing of a Transavia plane in 1997 with very strong cross winds. Obviously, it is important for airports that sufficient runway capacity is available under various wind directions. An underestimate of wind speeds and their directions may mean that wrong decisions are taken on the design of airports in terms of the capacity and orientation of runways. The Netherlands Bureau for Economic Policy Analysis (2002) has estimated that in the case of Schiphol a 'wrongly' configured system of runways – implying that the number of hours that the airport cannot be used is unnecessarily long – may lead to a negative welfare effect in the range of .6 and 2.8 billion Euro (net present value in 2000 Euro for the period 2002 to 2040), where the variation depends largely on the underlying assumptions with respect to economic development and global competition. However, wind is not the only factor. A good example of economic loss due to other types of bad weather is San Francisco International Airport. A study by Eads et al. (2000) shows that poor visibility in the summer months and rain storms in the winter months lead to substantial delays and numerous cancellations. Compared to good weather, cancellations per day increase by a factor 2-3 when weather is bad in the morning, and by a factor 3-4 when weather is bad all day. Similar figures hold for the number of delay minutes per flight operated. Although these figures are based on fairly simple counts, they were gathered over two entire years, thereby reducing the probability that the patterns were caused by other factors.

These figures illustrate that the impact of weather can be substantial. However, since the construction of San Francisco Airport differs from other major airports in the United States, caution is required in generalizing the results. At San Francisco the parallel runways are much closer than at other airports, which is why visibility is required by the Ministry of Transport and why lack of visibility leads to capacity restrictions. Most other airports in the US do not have this restriction and certain types of weather have less of an impact there. Still, weather plays a crucial role in the US aviation sector. Kulesa (2002) estimates that weather causes 70% of all delays while also being an important contributing factor in 23% of all aviation accidents. Similar results are obtained by Changnon (1996), who shows that rain had a substantial increasing effect on the number of departures with a delay of at least 30 minutes at Chicago O'Hare airport at the end of the 1970's. He also includes figures from the National Transportation Safety Board, which confirm that adverse weather has an increasing effect on aircraft accidents, especially those with fatalities. Total annual monetary costs associated with weather-related accident damage and injuries, delays and unexpected operating costs are estimated at $ 3 billion in US aviation (Kulesa, 2002).[15]

7. Road transport: Traffic safety and travel times

In this section we pay special attention to the effects of weather on road accidents and congestion and travel time. Obviously, these relationships are intertwined, making the relation between weather, traffic accidents and congestion an interesting but complex one. Direct empirical evidence on this complex set of relationships is scarce, however.[16] Most studies in this area focus primarily on the partial relationships between weather and accidents and weather and congestion. In the subsections below we discuss empirical evidence on these partial relationships and their possible interactions.

7.1 Accident frequency and severity

It is clear that (changes in) weather conditions have an effect on road safety. Several weather variables appear to be important. Stern and Zehavi (1990) investigate the relationship between hot weather and traffic accidents. They conclude that the risk of an accident increases with increasing heat-stress conditions. The largest increase was found to be in the category of single-vehicle accidents (see also Maycock, 1995; McDonald, 1984; Welch et al., 1970). Also fog and wind may have an increasing effect on the number of accidents (see, e.g., Edwards, 1996; Hermans et al., 2006). However, by far the most important variable is precipitation. Empirical evidence on the impact of rain and snow on the frequency and severity of road accidents is abundant. Although studies employ a wide variety of methods (least squares, Poisson and negative binomial regressions, matched-pair approach, mean differences, wet pavement indices) and display a fairly wide variety of outcomes in a quantitative sense, most of them indicate a positive relationship between precipitation and frequency of road accidents (see, e.g., Brodsky and Hakkert, 1988; Chung et al., 2005; Edwards, 1996; Eisenberg, 2004; Jones et al., 1991; Levine et al., 1995; Satterthwaite, 1976; Shankar et al., 2004, 1995). Rather extreme increases in road accidents and injuries due to precipitation are found by Andrey et al. (2003) using data from mid-sized Canadian cities. On average, precipitation increases the number of accidents by 75% and the number of related injuries by 45%, with snowfall having a more substantial effect than rainfall.[17]

An issue that appears to mediate the impact of rain and snow on road accidents is lagged precipitation. Eisenberg (2004) shows that lagged precipitation, i.e., rainfall the day or days before, substantially reduces the impact of precipitation on road safety, implying that rainfall leads to a stronger increase in the number of fatal accidents after a dry spell. This is most likely caused by the fact that precipitation clears the oil that accumulates on roads during dry periods, thereby making roads slippery. It is also possible that people adjust their driving behavior slowly, implying relatively risky driving behavior in rainy conditions after a dry spell. A similar lagged precipitation effect is found by Levine et al. (1995) and Brodsky and Hakkert (1988).

Although precipitation increases accident frequency, it appears to decrease accident severity. For instance, using negative binomial regressions, Eisenberg and Warner (2005) estimate the effects of snowfall on US traffic crash rates between 1975 and 2000. They find that snow days had more nonfatal-injury crashes and property-damage-only crashes, but fewer fatal crashes than dry days. Andrey et al. (2003) also find that the increase in the probability of an injury due to rain and snow is lower than the increase in the probability of an accident. Results by Fridstrøm (1999, Chapter 6) for Norway show a similar pattern; snow increases the number of injury accidents but decreases the number of fatalities per accident. For rainfall both the number of accidents and the number of fatalities decrease. Finally, Khattak et al. (1998) use an extensive dataset with single-vehicle and two-vehicle traffic accidents in North Carolina in the period 1990 to 1995. They estimate an ordered probit model in which they distinguish between four levels of severity, i.e., fatality, severe injury, moderate injury, no injury. The dummy variable on adverse weather (rain, snow, sleet, fog) has a statistically significant but small negative impact on accident severity, i.e., accidents are less severe in adverse weather. The effects of a wet and a snowy or icy road surface are much larger, however. The mediating effect in the observed pattern is likely that precipitation, and adverse weather in general, reduces traffic speed, thereby reducing the severity of an accident when it occurs.[18]

7.2 Congestion, travel time and travel time reliability

Most studies show a (substantial) reduction in traffic speed due to adverse weather, and especially precipitation. For example, results from a study by Martin et al. (2000) range from 10% speed reduction in wet conditions to 25% speed reduction in wet and slushy conditions. Hranac et al. (2006) use detailed traffic and weather data from 2002 to 2004 for the Baltimore, Seattle and Minneapolis-St. Paul metropolitan areas. Light rain causes reductions in free-flow speed and speed-at-capacity around 3% and 9%, respectively. Reductions generally increase with rain intensity, with maximum reductions around 6-9% and 8-14%, respectively. For snow the effects are larger; light snow causes reductions in free-flow speed and speed-at-capacity of 5-16%. Finally, Maze et al. (2006) use a dataset including four years of traffic data from the freeway system in the Minneapolis/St. Paul metropolitan area and weather data from three weather stations nearby the freeway network. They show that rain, snow and reduced visibility cause clear reductions in traffic speed; up to 6% for rain, up to 13% for snow, and up to 12% for reduced visibility.

There are some studies, however, that report slightly different results. For example, Lamm et al. (1990) find that there is no effect of wet pavements on traffic speed on rural highways in the New York state area. An important reason for this result is probably that only the speed of cars with a minimum time gap of 6 seconds were used, the focus of the study being to assess the purely behavioral response of drivers to wet pavements. This result seems to be more general applicable. Ibrahim and Hall (1994) use a dummy variable technique to analyze the effects of adverse weather on the speed-flow and flow-occupancy relationships. Although the impact of heavy snow is substantial and causes a reduction in free-flow speed of 38-50 km/hour, the impact of heavy rain on free-flow speed is limited at 5-10 km/hour. Also Unrau and Andrey (2006) find small rain effects at low volumes and large effects at high volumes. Furthermore, based on data from a national transport survey and local weather conditions in the Netherlands for 1996, Sabir et al. (2008a) employ panel data techniques to estimate the effect of adverse weather conditions on traffic speed. Although temperature and wind have small or no effect (see also Maze et al., 2006), the impact of snowfall is notable, with traffic speed reductions of around 7 percent. Using generally accepted values of time the associated welfare loss is estimated at 22 eurocent per commuting trip. Again, the effects of rain are small, except for trips made during rush hours in congested areas, where speed reductions are around 10 to 15 percent. The associated welfare loss is estimated at 88 eurocent per commuting trip.

In conclusion, the effects of temperature and wind on traffic speed appear to be small or not existent. Also the effect of rain on free-flow speed appears to be small, suggesting that the purely behavioral response of drivers to rain is limited. Likely the behavioral response is larger for heavy rain and snow. Furthermore, although the estimates from different studies are difficult to compare in magnitude, the impact of rain and especially snow on traffic speed at already congested routes and during peak hours appear to be substantial.[19]

Next to having an impact on mean travel time, adverse weather conditions may influence travel time reliability as well. This is an issue that has become increasingly important in transportation planning and research during the last two decades. In the literature travel time reliability may be measured in several ways, e.g., by statistical range methods, tardy-trip measures and probabilistic measures. Studies that analyze the impact of weather on reliability are scarce, however. An exception is a study by Tu et al. (2007) for the Netherlands, who analyze the impact of rain, snow, ice, fog and storm on travel time variability, which is measured as the difference between the 90th and 10th percentile of travel times on a specific route. They find that, on average, rain, snow, ice, fog and storm increase travel time variance. It is questionable, however, whether travel time differences at the route level are a good measure of travel time reliability, which is preferably measured at the trip level. It is likely that this study simply picks up that part of the car users drive slower under certain circumstances, which would reflect an individual specific change in travel time rather than a change in travel time reliability. Clearly, additional research is needed.

7.3 Discussion

Adverse weather conditions, and especially rain and snow, increase the number of road accidents, but appear to decrease their severity. They also cause traffic to slow down, although less so at free-flow speed, and increase the number and intensity of traffic jams, leading to substantial time losses by road users. Although these insights are clear enough in themselves, the net impact of climate change through changes in weather conditions on road transport is ambiguous. Increases in temperature will decrease the probability of snowfall, thereby likely decreasing congestion and improving traffic safety. However, whereas average rainfall may decrease, extremes are likely to increase, ultimately making the consequences for congestion, traffic jams and traffic safety uncertain, both in terms of direction and magnitude. Additional insights into the magnitude of the various effects is needed to make more accurate assessments on these issues.

8. Behavioral responses in passenger and freight transport

In transport behavioral reactions to adverse weather may occur in various ways. We can order them according to the well known basic dimensions of trip generation, trip distribution, modal choice, route choice, temporal choice, and speed choice (De Dios Ortúzar and Willumsen, 2001). With respect to the former two it is plausible that under adverse weather conditions certain trips are cancelled, that shopping occurs nearby rather than further away (distribution short run) and that average commuting distance declines (distribution long run). Regarding mode choice decisions car drivers may, for instance, be inclined to shift to public transport when precipitation increases congestion on roads. Another possibility is that people adjust their route choice based on expectations about changes in generalised transport costs of route choice alternatives. Travelers may furthermore change their time of departure, for example postponing a trip until it stops raining. The last dimension of change concerns speed choice. This choice element, already addressed in the previous section, can be considered as an instrument for car users to correct for the risk changes that occur under extreme weather conditions.[20] Despite the many possible behavioral responses by travelers to adverse weather, the available empirical evidence is relatively limited. Most studies focus on trip generation in road transport and regarding bicycle use, mode choice decisions and speed choice in road transport. As the latter has already been addressed in Section 7, below we subsequently discuss the other issues.

8.1 Traffic volume on roads

Changes in traffic flow and volume reflect changes in demand for transport, changes in route choice and postponement of trips. Parry (2000) notes that during days with snow, inessential journeys are postponed or curtailed. Although this is generally confirmed by the available empirical evidence, studies seem to disagree on the magnitude of the effect. Al Hassan and Barker (1999) find an average reduction of traffic volume in Scotland of approximately 15% when roads are covered with snow and a reduction of 4.6% on days with the highest rainfall. Keay and Simmonds (2005) find an overall reduction in traffic volume in Melbourne of 1.35% on wet days in winter and of 2.11% on wet days in spring.[21] Their results also show an overall volume reduction of 2-3% for 2-10 mm of rain during daytime, with reductions in spring somewhat larger than those in winter. Fridstrøm (1999, Chapter 4) analyzes determinants of vehicle kilometers in Norway and finds a strong seasonal impact. The more minutes of light per day and the higher the mean monthly temperature, the higher the number of vehicle kilometers (elasticities are equal to .141 and .068, respectively). The number of days of snowfall per month has a negative effect on the total number of vehicle kilometers; the elasticity is –.025. The consequences of snowfall for specifically freight transport are more substantial; the elasticity is –.067. Because functional forms for the relationships under investigation are largely unknown but likely nonlinear, Box-Cox parameters were estimated. In each case the estimated parameter indicates that the elasticity increases with the initial level of the relevant variable, e.g., a one percent increase in snowfall frequency causes a more substantial decrease in vehicle kilometers at higher initial snowfall frequencies.

One of the mediating factors in the effect of adverse weather on travel demand may be the purpose of a trip. Some evidence for this is provided by Chung et al. (2005), who analyze the impact of rainfall on travel demand on the Tokyo Metropolitan Expressway, using traffic counts and rainfall measured on a daily basis for the period 1998 to 2004. They find that travel demand on weekdays decreases on average by 2-4% as rainfall increases from 1 to 30 millimeter per day. The effects on Saturdays and Sundays are much larger, ranging approximately from 4-14% and from 4-8%, respectively. Changnon (1996) obtains similar results for the Chicago area, although the data used are less recent. Using data from three years at the end of the 1970's, he finds that rain has a negligible effect on traffic volume during weekdays (less than 1%), but reduces traffic volume by more than 9% during weekends.

Some extreme effects can be found in Hanbali and Kuemmel (1993) who analyze the impact of winter storms on traffic volume, and find that the decrease in traffic volume (in %) is large and nearly proportional to the amount of snowfall. Specifically, traffic flow reduction during weekdays for < 25 mm of snow is 7-17%, for 25-75 mm of snow it is 11-25%, for 75-150 mm of snow it is 18-43%, for 150-225 mm of snow it is 35-49%, and for 225-375 mm of snow it is 41-53%. Trip purpose again appears to be of relevance, traffic volume reduction during peak hours being less than during off-peak hours, and less during weekdays than during weekends. As such, trip purpose and specifically the distinction between work and business related transport and leisure transport appears to be an important segmentation in the transport market.

We conclude that, on the one hand, increasing frequency of extreme precipitation events under climate change may substantially decrease the number of trips on specific days, especially those for leisure purposes. On the other hand, increasing average temperatures and a decrease in average rainfall (depending partly on the region) will likely increase leisure trips. Given the relatively limited changes in averages, these effect are likely small, however.

8.2 Bicycle use

There is some evidence that changes in temperature, precipitation and wind affect utility attached to bicycle use. Richardson (2000) finds that rainfall and both low and very high temperatures decrease the number of cycling trips. This pattern appears to be fairly general; low temperatures, strong wind and precipitation have a negative impact on the use of the bicycle (see, e.g., Emmerson et al., 1998;

Goetzke and Rave, 2006; Sabir et al., 2008b; Winters et al., 2007). Bergström and Magnusson (2003) perform a survey among a thousand employees of four major companies in two Swedish cities. They find that there is a large decrease in the number of bicycle trips (–47%) and a large increase in car use (+27%) for commuting purposes during winter (see also Öberg et al., 1996). Moreover, temperature and precipitation were among the most important factors for those who cycled to work in summer but not in winter. Although bad weather certainly causes a reduction in the number of people who use the bike for commuting purposes, there is strong evidence that recreational cycling is more affected by bad weather than utilitarian cycling (see Richardson, 2000; Bergström and Magnusson, 2003). Whereas most studies use a time series approach, Rietveld and Daniel (2004) perform a cross section comparison. They find that wind speed affects bicycle use in The Netherlands; municipalities with strong winds are found to have lower annual bicycle use than municipalities with moderate wind speeds.

8.3 Mode choice decisions: Passenger transport

As is clear from previous sections, the net effect of climate change on infrastructure disruptions, and the associated changes in transport costs, is ambiguous for most transport modes. The impact of climate change on modal choice through infrastructure disruptions are therefore equally uncertain and empirical insights on this particular issue are absent. However, there are some insights into short run mode choice decisions under different weather conditions. Khattak and De Palma (1997) conduct a stated preference study among Brussels commuters in 1992, assessing their mode choice decisions under various circumstances. The results show that 69% of the respondents, next to their primary transportation mode, have access to an alternative transportation mode, but that only 5% actually switches between transportation modes according to season. This suggests that changes in weather patterns from summer to winter have only a small impact on modal choice, and specifically points to a limited substitution between car and public transport. This is not to say that no behavioral change takes place. More than half of the automobile users indicate that they would change mode, departure time or route under adverse weather conditions, of which changes in departure time appears to be the most popular option. Further analysis suggests that flexibility of the activity is a very important factor for a change in mode choice. Also worth noting is that the use of weather forecasts have only a small increasing and statistically insignificant impact on the probability of a change in mode choice. A similar pattern emerges from an ordered probit analysis on 'changes in departure time due to adverse weather', with the added feature that greater flexibility in arrival time and departure at work time has a large impact on changing departure time.[22] Since the sample used for these ordered probit analyses is rather small (N = 166) and includes car users only (i.e., car is primary transport mode), caution is required in generalizing the results.[23]

Results from a revealed preference study by Aaheim and Hauge (2005) on the impact of weather on travel habits in Bergen (Norway) in 2000 suggests that the impact of weather on substitution between public and private transport is relatively small. The study also shows that travel distance decreases with precipitation, except for trips with commuting purposes. Therefore, although precipitation has a direct negative effect on the proportion of walking and biking trips, it has an indirect positive effect because of its decreasing effect on trip distance. The authors conclude that in some cases the indirect positive effect outweighs the direct negative effect. However, the study has several important drawbacks. Among others, it uses daily instead of hourly data on weather conditions, and observations are from 2.5 months only. Results should therefore be interpreted with caution.

Finally, using detailed trip information from a national transport survey and local and hourly weather conditions, Sabir et al. (2008b) estimate a multinomial logit model to analyze the impact of weather on mode choice in the Netherlands. The results suggest that strong winds and low temperatures discourage bicycle use and stimulate the use of the car and public transport. The reverse appears to be true for high temperatures. Precipitation has the most substantial impact on bicycle and car use, decreasing bicycle use and substantially increasing the use of the car. Although the results are insightful, a disadvantage of this study is that its analysis is based on mode shares, and as such does not distinguish between transport demand and mode substitution. Shifts in mode shares are thus interpreted as modal shifts, while they may also reflect cancellation of certain trips.

8.4 Mode choice decisions: Freight transport

Similar to the situation in passenger transport, the impact of climate change on mode choice decisions in freight transport through infrastructure disruptions are uncertain. Empirical insights on this particular issue are therefore also largely absent. An exception is a study by Jonkeren et al. (2008). Climate change is expected to affect inland waterway transport in most main natural waterways in Europe. For the river Rhine it is expected that in summer, more and longer periods with low water levels will occur, which was shown to increase transport prices per ton (see Section 5). One possible consequence of these higher transport prices is a deterioration of the competitive position of inland waterway transport compared to rail and road transport and thus a change in modal split. To study this issue the Jonkeren et al. (2008) study use a GIS based network model, which provides a tool for detailed analysis of freight transportation over extensive multimodal networks. They assess the effect of low water levels on the cost functions of transport operations for inland waterway transport in North West Europe under several climate scenarios. Assuming no climate change consequences for road and rail transport, it turns out that the modal shift effect is limited. Under the most extreme climate scenario, inland waterway transport is estimated to loose about 3.2 million tons annually in the part of the European inland waterway transport market considered, which amounts to about 5% of the current amount transported by barge in this market. Ultimately, modal shifts depend on relative transport costs and more detailed insights into the climate change consequences for costs of rail and road transport are needed. However, given that the direction of net effects for these two modes is highly uncertain, it is not likely that, on average, changes in transport costs will be substantial enough to cause large long run changes in the modal split in freight transport.

8.5 Discussion

Although several studies on behavioral responses to adverse weather are available, it is clear that the impact of weather conditions on destination choice, route choice and departure time are under researched. Also the empirical evidence is scarce, many studies have important drawbacks, and many insights are lacking, implying that strong inferences on behavioral change in transport due to climate change are not possible at this point in time. Furthermore, most available studies focus on current weather conditions. When one is interested in the potential long run effects of climate change for transport, the impact of seasonal patterns are probably more relevant. For example, studies that try to gain insight into instantaneous responses to adverse weather, e.g., transport demand and mode choice responses to rain or snow, do not take on board the question whether the number of trips is actually reduced, or that people just make the trip at a later time during the day or the week. Clearly more detailed research is needed to obtain the necessary insights into behavioral responses in transport to climate change related shifts in weather conditions.

9. Summary and conclusions

To date, the consequences of climate change and weather conditions for the transport sector have received relatively little attention in the literature. Still, it is widely known that transport systems on the whole perform worse under adverse and extreme weather conditions. This is especially true in densely populated regions, such as many coastal areas around the globe, where one single event may lead to a chain of reactions that influence large parts of the transport system. In this paper we have provided an overview of empirical findings on the impact of climate change and adverse weather on transport. Despite mixed evidence on many issues, several patterns can be observed.

On a global scale especially the increase in temperatures may influence patterns in tourism and skiing holidays, with the associated changes in passenger transport. We may also expect global shifts in agricultural production, with associated changes in freight transport. The predicted rise in sea levels and the associated increase in frequency and intensity of storm surges and flooding incidences may furthermore be some of the most worrying consequences of climate change, especially for coastal areas. Empirical research for Europe is limited, but research for the US East Coast and Gulf area shows that the effects on transport and transport infrastructure may be substantial. However, because flood defenses that are already in place are included in none of the studies, the insights may have limited value for assessing future flood-risk and exposure for specific locations, and likely also overestimate total exposure and damages due to climate change.

Climate change related shifts in weather patterns may also affect infrastructure disruptions. For road transport most studies focus on traffic safety and congestion. With respect to traffic safety by far the most important variable is precipitation, most studies finding that precipitation increases accident frequency, but decreases accident severity. The mediating effect in here is likely that precipitation reduces traffic speed, thereby reducing the severity of an accident when it occurs. Furthermore, most studies show a reduction in traffic speed due to precipitation and especially snow. Interestingly, the effect is particularly large during peak hours and on congested roads. The few existing insights for rail transport show that high temperatures, icing, and strong winds, among others, may cause considerable delays. For the aviation sector, wind speeds, wind direction and visibility have clear effects on safety and delays and cancellations. This has large cost implications, both for airlines and travelers. However, implications of climate change on wind speeds but especially on wind directions and developments with respect to mist, fog and visibility are highly uncertain. Finally, changes in temperature and precipitation have consequences for riverine water levels. Low water levels will force inland waterway vessels to use only part of their maximum capacity, which may considerably increase transportation costs in the future.

It is clear that changes in weather conditions due to climate change will affect the competitive positions of the different transport modes, both within passenger and freight transport. However, although the effects on the inland navigation sector will most likely be negative, the net impact for most transport modes are ambiguous, and like also region-specific. First, we observe opposing effects, e.g., with respect to traffic safety and congestion in road transport and infrastructure disruptions in rail transport, the magnitudes of which are largely unknown. Second, outcomes of the various climate change models and scenarios and the associated changes in weather conditions display wide variation. Moreover, insofar as regional climate change assessments are available, the differences are large. Finally, the large majority of the studies on the impact of climate and weather focus on instantaneous or short term impacts. Less attention is paid to impacts at the seasonal level, or the long run effects as they can be detected by comparing regions that operate under different climate conditions. Research into these directions is recommended to develop a fuller view on the consequences of climate change for the transport sector.

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Appendix A. Regional differences in climate change

Especially the large uncertainty about changes in circular wind flows and shifts in oceanic currents make that changes in regional temperature and precipitation patterns, but also changes in frequency and intensity of tropical storms, are difficult to predict. Moreover, some regional models are more extensive and detailed than others, and for some regions more and more reliable historic data are available than for others. Table A1 reports the effects of climate change for various regions across the globe as predicted by a recent IPCC study (see Christensen et al., 2007).

Table A1. Predicted effects of climate change for various regions across the globe

Region	**Climate change effects**
Africa	▪ Nearly 1.5 times global mean increase in temperature. ▪ Dryer in the Mediterranean and southern Africa, increasing rainfall in East Africa. ▪ Large uncertainty with respect to precipitation (patterns) and with respect to changes in spatial distribution and frequency of tropical cyclones.
Europe	▪ Slightly higher increase in mean temperatures than global mean. ▪ Warming in northern Europe largest in winter, for the Mediterranean largest in summer. ▪ Lowest winter temperatures increase more than average temperatures in northern Europe, highest temperatures increase more in summer than average temperatures in southern and central Europe. ▪ Mean precipitation increase in northern Europe and decrease in most of the Mediterranean area. ▪ Extremes in precipitation very likely to increase in northern Europe. ▪ Increase in risk of summer drought in central Europe and Mediterranean. ▪ Changes in wind strength uncertain, although it is more likely that average and extreme wind speeds will increase. ▪ Duration of snow season and snow depth very likely to decrease.
Asia	▪ Increase in temperatures higher than global mean. ▪ Summer heat spells will be longer, more intense, and more frequent in East Asia. ▪ Most of Asia will experience an increase in precipitation, either during summer or winter. ▪ Increase in frequency of intense precipitation events in parts of South Asia and in East Asia. ▪ Extreme rainfall and winds due to tropical cyclones likely increase in East, Southeast and South Asia.
North America	▪ Slightly higher increase in temperatures than global mean. ▪ Warming largest during winter in northern regions, and largest during summer in the Southwest. ▪ Mean precipitation likely increases in Canada and northeast USA, and likely decreases in southwest USA. ▪ Snow season and snow depth very likely decrease in most of North America.

Central and South America	▪ Mean increase in temperature by and large similar to global average. ▪ Precipitation likely to decrease in central America. ▪ Large local variation in precipitation in mountainous areas. ▪ Large uncertainty with respect to annual and seasonal mean rainfall in northern South America.
Australia and New Zealand	▪ Mean increase in temperature by and large similar to global average. ▪ Increased frequency of extreme high daily temperatures, and decrease in the frequency of cold extremes. ▪ Precipitation likely to decrease in Southern Australia in winter and spring, likewise for Southwest Australia in winter. ▪ Changes in rainfall uncertain in northern and central Australia, although extremes are very likely to increase. ▪ Precipitation likely to increase in the west of the South Island of New Zealand; ▪ Increased risk of drought in southern areas of Australia.
Polar regions	▪ Mean warming very likely exceeds global mean, and is largest in winter and smallest in summer. ▪ Arctic precipitation increases, likely more in winter than in summer. ▪ Arctic sea ice likely to decrease in extent and thickness (uncertain how Arctic Ocean circulation will change). ▪ Antarctic temperatures and precipitation are likely to increase. ▪ Uncertainty with respect to frequency of extreme temperature and rainfall events in polar regions.

Source: Christensen et al. (2007)

Endnotes

[1] It is worth noting that the effects of climate change on welfare are not necessarily negative; for example, higher temperatures imply lower costs for heating and higher agricultural productivities in moderate and cold zones. The general expectation is that the balance of the two is negative in countries in warm zones and positive in more moderate zones. Also in the transport sector a mixture of negative and positive effects may be expected. In both cases they may lead to adaptation strategies at the supply and demand side of the markets for transport services.
[2] A review of approaches to reduce emissions in the transport sector, with a focus on car use, road freight and aviation, is provided in Chapman (2007).
[3] We have excluded the impact of climate change and changes in weather conditions on infrastructure maintenance. In our view this is more an engineering issue than an economic one, although of course economic decision making is involved in adaptation to possible climate change effects. Some preliminary insights are given in Instanes et al. (2005) and Transportation Research Board (2008, Annex 3-1).
[4] Thermal expansion accounts for 70% to 75% of the predicted rise in sea levels. Most of the remainder is due to the melting of glaciers, ice caps and the Greenland ice sheet.
[5] For more details on flooding frequencies and intensities in 2100 at Newark Airport, Holland Tunnel, JFK Airport, LGA Airport, Lincoln Tunnel and the New York Passenger Ship Terminal, see Figure 9.6 in Jacob et al. (2007).
[6] In an earlier version of this study the estimates were taken from the Third Assessment Report by the IPCC. As mentioned before, these estimates do not take into account possible melting of the Greenland and West Atlantic ice shelves. Low estimates for 2025, 2050, 2075 and 2100 are, respectively, 6 cm, 13 cm, 21 cm and 30 cm. High estimates for these years are, respectively, 6.5 cm, 17.5 cm, 31 cm and 48.5 cm. In a more recent version of this study the Fourth Assessment report was available and a sea level rise of 59 cm in 2100 was also included in the analyses.
[7] Note that in this study only the direct effect of sea level rise is incorporated. The indirect effect of sea level rise through its impact on storm surge levels is omitted, implying that damage figures are underestimates.
[8] See Gössling and Hall (2006) for a discussions of uncertainties in predicting future tourism flows.
[9] Mulherin et al. (1999) use Monte Carlo simulation to predict time and costs of transport along the Northwest Passage. They show that sea-ice cover conditions are the most influential parameters in determining time and costs of shipping along the Northwest route. More specifically, ice-free conditions allowed a ship to transit from Murmansk to the Bering Strait in 37% of the time required under normal conditions, on average. This implies that climate change may present large economic opportunities.
[10] Climate model exercises by Lofgren et al. (2000) show that small increases in water levels are also possible.
[11] See Millerd (1996) for an earlier assessment of the impact of water levels on operating costs of inland shipping in the Great Lakes area.
[12] Although at first sight these cost figures appear low in an absolute sense, note that this study deals with only a small part of the Mississippi related transport market.
[13] Lofgren et al. (2000) show that a positive effect of climate change may be a substantial reduction in ice cover on the Great Lakes. They do not assess the (potential) positive consequences for the commercial shipping sector.
[14] Approximately 300 million tonnes are transported over the Rhine each year, of which around 80 million tonnes pass by Kaub. The study therefore covers around 27% of the entire Rhine market (see Jonkeren et al., 2007).
[15] Increases in temperatures lead to a decrease in air density. This may lead to cargo loss, increased length of runways and an increase in fuel needed (TRB, 2008).
[16] A notable exception is a study by Golob and Recker (2003), who identify relationships between accident characteristics, traffic and traffic-flow characteristics, and weather and lighting conditions. They find that weather and lighting conditions are related to accident characteristics directly and indirectly through their impact on traffic characteristics, such as traffic flow and traffic speed.
[17] Knapp et al. (2000) analyze the impact of winter storms on traffic accidents. They collect data for seven interstate roadway locations with nearby weather stations in Iowa between 1995 and 1997. In this study even more extreme estimates are found, accident frequency being around ten times as large as under normal circumstances. A Poisson model analysis furthermore shows a substantial increase in accident frequency for increasing snowfall intensities and a small but statistically significant impact of storm event duration.
[18] Where traffic speed is likely a relevant mediating factor in accident severity, traffic volume is likely more relevant in accident probability per time period.

[19] Extremes can be found in Knapp et al. (2000), who analyze the impact of winter storms on traffic volume. They collect data for seven interstate roadway locations with nearby weather stations in Iowa between 1995 and 1998. Using several criteria (snowfall intensity more than 0.2 inch or 0.5 centimeter per hour, minimum of four hours duration, event did not occur on or near a holiday) they identify 64 winter storm events for a total of 618 hours. The impact for a particular event is measured as the difference between the winter storm event traffic volume and the comparable average monthly non-storm volume for that time period and day of the week. On average a substantial daily (hourly) volume reduction of 29% (33%) was found, but variability was large. Using multiple regression analysis shows that lower impacts are found for events of shorter duration, while higher impacts are found for events with higher average wind speeds and larger maximum wind gusts.

[20] We note that these behavioral adjustments are the result of choices of travelers. There is another type of behavioral change that can take place, namely, decisions of suppliers of transport services to adjust the level of service to the weather conditions.

[21] Hogema (1996) presents similar findings, with reductions in traffic volume of 2-3% on wet days opposed to dry days. However, the differences between dry and wet days were statistically insignificant without exception.

[22] In general the results suggest that people with greater flexibility in arrival times at work do not change their departure time due to adverse weather because it does not matter whether they arrive late or not. Greater flexibility in leaving work early does lead to changes in departure times, suggesting that in adverse weather people who can will leave home and work earlier to avoid the morning and evening peaks.

[23] De Palma and Rochat (1999) conduct a similar survey among Geneva commuters. The patterns found are like the ones in Khattak and De Palma (1997). Weather leads to changes in mode choice, route choice and departure time choice, with the latter being most important. Furthermore, weather forecasts again did not play a substantial role.