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Adaptation to Climate Change in the Transport Sector

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ABSTRACT *In this study, we review the literature on climate change adaptation measures in the transport sector. Many of the measures proposed are rather conceptual and far from concrete, probably due to the fact that climate change effects on transport are either unknown or highly uncertain. Given the limited information on the potential magnitude of climate damages and the various uncertainties involved, postponement of adaptation investments may well be the most sensible strategy at the moment, especially when investments are substantial and irreversible. Furthermore, monitoring of relevant climatic changes and ongoing research into climate change effects are important elements of a pro-active adaptation strategy. Irreversible decisions, such as the ones on spatial organization, likely require a more active strategy, e.g. in the form of making spatial reservations. We further discuss the interdependency between optimal mitigation and adaptation, an issue that is often overlooked in the literature. Finally, most operators and governmental bodies are not used to dealing with risk and uncertainty, and generally base their decisions on single risk values only, likely leading to under- or overinvestment. We discuss several relevant topics in this area and highlight methods that can be used to better deal with these issues.*

JEL Classification: D81; R40; R41; Q54

1. Introduction

Until recently, the overwhelming majority of climate change research was focused on mitigation. However, most scientists have come to the conclusion that even under extreme greenhouse gas (GHG) mitigation efforts certain climatic changes have become inevitable (see IPCC, 2007a, 2007b, 2007c). As a consequence adaptation has been added to the scientific and political agenda in more and more countries.

A sector that has received little explicit attention in this respect is the transport sector, mainly because important knowledge gaps exist on the effects of climate change on transport, both in terms of direction and magnitude. Still, it is clear that transport systems on the whole perform worse under adverse and extreme weather conditions. This is especially true in regions with dense infrastructure networks and dense populations, where one single event may influence large parts of the transport system and affect substantial parts of the population. This

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study presents an overview of issues that are relevant for climate change adaptation, with a focus on the transport sector.¹ In doing so we review both the scientific literature and policy (related) documents.

The remainder of this study is organized as follows. In Section 2, we review the physical consequences of climate change for transport, while Section 3 reviews the literature on climate change adaptation options in the transport sector. Section 4 is dedicated to the question of how much adaptation should be done. Here, we discuss optimal adaptation levels and their interdependency with mitigation residual climate change damages. In Section 5, we add complexity to the insights of Section 4 by discussing the risks and uncertainties inherent to climatic change. We also discuss several methods and approaches to deal with these issues. Section 6 concludes.

2. Effects of Climate Change on Transport

Important climate changes for the transport sector as predicted by most of the existing climate models are an increase in global temperatures, changes in precipitation patterns, sea level rise, and increases in weather variability and weather extremes. Uncertainty on climatic changes is large, particularly with respect to local predictions on future weather conditions and future weather variability. Also climatic changes differ between regions (see, e.g. Appendix A in Koetse & Rietveld, 2009). Therefore, although predicted global mean climatic changes are important, the increase in variability and extremes and the uncertainty on and regional deviations from the global means are probably at least as relevant for analysing climate change impacts.

It is widely known that transport systems on the whole perform worse under adverse and extreme weather conditions, implying increased vulnerability of these systems under current climate change predictions. This is especially true in regions with large network and population densities, 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. Koetse and Rietveld (2009) provide a survey of the empirical literature on the effects of climate change on transport. An important finding of this study is that many of these effects are ambiguous, both in terms of direction and magnitude. Most of the ambiguity is caused by varying effects of predicted future weather conditions. For example, in many predictions average rainfall in the summer period decreases, while rainfall extremes during this period increase both in frequency and intensity. Both developments have opposite effects on, e.g. traffic accidents and congestion, making the net effect uncertain.

Despite the many ambiguities and uncertainties, several patterns can be distinguished. On a global scale, increases in temperatures may influence patterns in tourism and skiing holidays, leading to changes in passenger transport (e.g. Elsasser & Bürki, 2002; Nicholls & Amelung, 2008). We may also expect global shifts in agricultural production, implying changes in freight transport patterns (e.g. Easterling et al., 2007; Fischer, Shah, & Van Velthuisen, 2002). Sea level rise and the resulting increases in frequency and intensity of storm surges and flooding incidences are among the most worrying climate developments, 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, including ports and airports, can be substantial (ICF, 2008;

Jacob, Gornitz, & Rosenzweig, 2007; Kafalenos & Leonard, 2008; Nicholls et al., 2008). The same holds for many developing countries (Dasgupta, Laplante, Meisner, Wheeler, & Yan, 2007).

With respect to road transport most studies focus on traffic safety and congestion. Precipitation (rain and snow) is by far the most important weather variable for traffic safety. Most studies find that precipitation increases accident frequency, but can also decrease accident severity. The mediating effect here is likely that precipitation reduces traffic speed, thereby reducing the severity of an accident when it occurs (e.g. Brijs, Karlis, & Wets, 2008; Chung, Ohtani, Warita, Kuwahara, & Morita, 2005). In some parts of the world substantial positive safety effects may be expected due to milder winter conditions (e.g. Andersson & Chapman, 2011). With respect to congestion many 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 (e.g. Maze, Agarwal, & Burchett, 2006; Sabir, Van Ommeren, Koetse, & Rietveld, 2011). Recent insights for rail transport show that both positive and negative effects may be substantial (e.g. Dobney, Baker, Chapman, & Quinn, 2010; Dobney, Baker, Quinn, & Chapman, 2009), so net consequences are highly region specific. For the aviation sector, wind speeds, wind direction and visibility have clear effects on safety and delays and cancellations (e.g. Eads et al., 2000; Pejovic, Williams, Noland, & Toumi, 2009), which have large potential cost implications for both airlines and travellers. Climate change consequences for wind speeds and especially for wind directions and mist, fog and visibility, are highly uncertain, implying that climate change consequences for specific regions and airports are difficult to assess. 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 capacity, which may considerably increase transportation costs in the future (see Jonkeren, Rietveld, & van Ommeren, 2007; Millerd, 2005; Olsen, Zepp, & Dager, 2005).

It is clear that changes in future weather conditions due to climate change will affect the competitive positions of different transport modes, both within passenger and freight transport. As already mentioned, however, the net impact for most transport modes is ambiguous and very much region-specific. Insights into behavioural reactions to future weather in passenger and freight transport are therefore limited. Several European studies show only limited mode substitution in passenger transport under changing weather conditions (e.g. Aaheim & Hauge, 2005; De Palma & Rochat, 1999). With respect to freight transport, Jonkeren, Jourquin, and Rietveld (2011) and Krekt et al., (2011) find that increasing prices of water transport due to low water levels may cause a modal shift from water to road and rail from 2% to 8% of total annual cargo volume. More knowledge on these behavioural reactions to climatic changes is important because those responses may mitigate the initial negative effects themselves, and because they provide insight into possible consequences of adaptation policies. Especially relevant in this respect are behavioural reactions to extreme weather events and the associated infrastructure disruptions.

3. Adaptation to Climate Change in Transport

Adaptation to climate change in transport has received little attention so far, and in those studies where transport is treated explicitly little insight is provided into the potential effectiveness of specific adaptation measures. Only a few countries have adopted specific national adaptation strategies. Exceptions to the rule are

Canada (Lemmen, Warren, Lacroix, & Bush, 2008), Finland (Marttila et al., 2005) and the UK (DEFRA, 2006). In the remainder of this section, we review the available literature on adaptation to climate change in transport.

3.1 *Adaptation Measures*

Contemporary policy documents mainly focus on adaptation of physical infrastructure. For example, increased extremes in precipitation may demand an increase in drainage capacity, and wider temperature ranges will affect the functioning of bridges and the maintenance costs of asphalt. Adaptation may therefore involve the use of different materials, different parameter settings, and increased drainage capacity (see Table 5.1 in TRB, 2008, for a list of infrastructure design adaptation measures). With respect to adaptation of rail infrastructure, Dobney et al. (2010) and Dobney et al. (2009) suggest that proper maintenance of track and track bed and proper setting of the stress-free rail temperature are the most efficient adaptation measures. Also for inland waterways, adaptation of the waterway infrastructure itself (e.g. canalization of the downstream part of the river Rhine) appears to be economically profitable (Krekt et al., 2011). An important question is whether relatively irreversible investments in infrastructure have lifetimes such that, given the pace of climatic changes, they might fail under the new climate parameters (see also Reilly & Schimmelpfennig, 2000). Some infrastructure elements have relatively short lifetimes compared to the period in which climate change is predicted to become potentially problematic. This implies that there are many opportunities for adaptation, and that many of the potential problems are relatively easily solved by simply incorporating climate change in regular maintenance, possibly with stricter design parameters because of wider extremes (TRB, 2008; Van Ooststroom, Annema, & Kolkman, 2008). For long(er)-lived investments and large investments that are sensitive to rapidly changing climate parameters, it is sensible to include climate change in planning decisions as soon as possible (Frankhauser, Smith, & Tol, 1999). Arguably many elements of transport infrastructure belong to this category. Adaptation of infrastructure design to sea level rise in Canada and coastal zone management in the USA and The Netherlands are interesting examples in this respect. Noteworthy is that in these cases adaptation is embedded in broader investment or adaptation programmes (Adger, Agrawala, & Qader Mirza, 2007).

Clearly, different elements of transport infrastructure have different technical lifetimes (see Table 4.2 in TRB, 2008), implying that sensible adaptation strategies will vary for different infrastructures. A more pressing problem may be that the planning horizon of most infrastructure operators is much shorter than the period over which climatic changes are predicted to become (potentially) problematic for the functioning of transport networks. For the shorter time horizons (e.g. less than 25 years) climate change predictions are highly uncertain, implying that there is a considerable possibility that adaptation investments that appear appropriate and profitable now given a certain climate prediction, turn out to be inappropriate and unprofitable ex-post (see Section 5).

With respect to specific adaptation measures of transport infrastructure, good examples are the elevation of road and rail infrastructure, increasing the height of bridges to allow transport at higher water levels, and canalization of waterways at specific bottlenecks to deal with low water levels (e.g. Demirel, 2011; Rietveld, 2012). An interesting study is De Bruin et al. (2009b), who identify 96 adaptation

options for The Netherlands based on a literature review and expert assessment. Adaptation options and strategies in the transport sector that are distinguished are:

- Coastal zone management;
- Change modes of transport and develop more intelligent infrastructure;
- Water management systems: emergency systems revision for tunnels and subways;
- Adaptation of highways and secondary dikes to create compartments;
- Protection of vital infrastructure;
- Enhancing capacity of locks and weirs;
- Design spatial planning – construct new housing and infrastructure;
- New design of large infrastructure;
- Design infrastructure for recreation and tourism – coastal areas.

Clearly, many of these elements consist of physical adaptation or (re)design of infrastructure, and represent strategic options for which a range of specific measures is available. In the De Bruin et al. (2009b) study, criteria such as necessity and effectiveness are used to rank the various adaptation options. Using this ranking, coastal zone management, changing modes of transportation and development of intelligent infrastructure appear to be among the more interesting adaptation options, although costs and benefits were not included in this ranking, mainly because insights into these issues are still largely missing.

One of the adaptation options mentioned in the list above, i.e. the design of infrastructure for recreation and tourism, is clearly aimed at *opportunities* that may arise due to climate change. In most studies the possible positive aspects of climate change, and the opportunities it may bring, are ignored. An increase in tourist attractiveness of certain regions because of higher temperatures is an obvious one, but other opportunities could be interesting as well. For example, increased flood risk around the globe may lead to increased demand for flood defences. Countries with a comparative advantage in this particular sector, may benefit.

With respect to air transport, there is large uncertainty on future changes in snow, ice, flooding and fog, all of which can affect airport operations and air transport. Also uncertainty on changes in wind direction is particularly high, as are the costs of inefficient configuration of airports. Making spatial reservations now may enable an effective response to climate change developments in the future. Since spatial claims are largely irreversible, making spatial reservations is likely an important element in any pro-active adaptation strategy, especially in densely populated areas (Rietveld, 2010). In this respect, reservations on elevated areas are essential, because low-lying areas may be inundated more frequently in the future, either because of sea level rise and storm surge in coastal areas, or because of more intense and more frequent extreme (weather) events. For example, given the critical role of infrastructure in dealing with extreme weather events, the regular use of such elevated areas could be such that at short notice they can be used as transport infrastructure (e.g. TRB, 2008). Spatial reservations are furthermore attractive because they are only costly in the sense that certain areas cannot be used, at least temporarily, for other (irreversible) activities. This means that these activities can still take place, but just at potentially less preferred locations.

3.2 *Weather Extremes*

Changes in average weather conditions are important for transport, but it is widely recognized that the increase in variability and in the frequency and intensity of extreme weather conditions are most problematic for transport, especially in the near future. In the TRB (2008) study it is stressed that future developments on climate extremes (e.g. heavy rainfall) increase the need for emergency transportation and evacuation, implying alternative means of transportation and alternative routes during weather extremes. More generally, an increase of redundancy within infrastructure networks is required (Kirshen, Ruth, & Anderson, 2008).

Weather extremes likely become problematic much earlier than changes in mean weather conditions, making adaptation to extreme weather conditions more urgent (e.g. Frankhauser et al., 1999; Kwadijk & Middelkoop, 1994). Research on transport effects of weather extremes is limited, mainly because data are inherently scarce. In any case, it is clear that in (re)designing infrastructure, adaptation to climate change implies that the choice of design standards of infrastructures should be such that they remain robust under various conditions. In this respect knowledge on the frequency and intensity of future weather extremes is essential, because they will determine the limits of capacity and effective functioning of infrastructure (Frankhauser et al., 1999; TRB, 2008).

Dealing with the negative consequences of adverse weather is already very common in actual practice. Dealing with climatic changes may therefore simply mean adjusting to increased frequency and intensity of (extreme) weather events. Just as weather is monitored for air transport operations, it may also be monitored for road, rail and inland waterway transport. With respect to new infrastructure, it is likely sensible to do construction at elevated locations. Especially in coastal areas, where demand for new infrastructure is especially large, the use of such locations could be a very sensible strategy.

3.3 *Costs and Benefits of Adaptation*

Although various climate change adaptation options in the transport sector exist, their costs and benefits are generally unknown. For example, in TRB (2008) an extensive list of concrete adaptation measures is given (see Annexes 5-1a to 5-1c), but no information is provided on costs and potential benefits of the measures, simply because the necessary information is missing or highly uncertain. De Bruin et al. (2009b) also recognize that insights into costs and benefits, especially those on indirect and external economic and environmental effects, are largely missing. Of course, the costs and potential benefits of adaptation measures may vary, depending on, e.g. region and climate change scenario chosen. However, quantitative estimates are essential to evaluate cost-effectiveness of adaptation options, so research on costs and benefits is important and even urgent in some cases (Adger et al., 2007; Tol, Frankhauser, & Smith, 1998). Monitoring climate change developments and climate change vulnerability of transport infrastructures is therefore crucial, especially with respect to weather extremes since these determine to a large extent the functioning of infrastructure networks, and thereby the effectiveness and cost-efficiency of infrastructure (re)design and other adaptation measures. Also the call for research on climate change impacts and vulnerability assessments, including the differences therein between vulnerable and less vulnerable regions, is widespread (e.g. COM, 2009; Frankhauser et al., 1999).

The literature on adaptation possibilities has focused primarily on Europe and the USA, or generally the global North. There are several differences with regions located in the global South that may be relevant for adaptation. First, regions in the global South may be more vulnerable to climate change, and effects may be larger in terms of geographical scale and number of people affected. Second, infrastructure networks are generally not as developed as in the North, and there is a greater emphasis on expansion. This may actually be an opportunity because incorporating climate change into new infrastructure construction is probably easier and less costly than for maintenance and retrofit of existing infrastructure. However, since many of these regions face pressing problems in the short run, making use of these opportunities is likely not straightforward.

3.4 *Public Versus Private Sector Adaptation*

Public sector adaptation is efficient when it takes account of private sector incentives for adaptation and when it equates marginal costs and benefits. When no market failures and externalities are present, and when markets do not display properties of a natural monopoly, private sector adaptation should suffice. However, for many elements of transport systems these properties do not hold, most importantly the infrastructure itself (network characteristics, many externalities, large costs, substantial safety issues). Further, because of the public good characteristics, transport infrastructure has a long history of public sector involvement. For these reasons, adaptation measures in the transport sector will and should to a substantial extent be taken by local and/or national governments.

Both markets and governments may display failures, and although monetary incentives for private parties may correct these failures to some extent, ultimately a mix of private and public parties is required for efficient adaptation. At this moment, most adaptation initiatives by public and private parties are still of an organizational/planning nature. For example, in the UK, the highways agency business plan includes a programme addressing the responses required for adaptation to climate change over the next 30–40 years. Also the UK rail sector has recognized the need for adaptation by increasing the resilience of the rail network to high winds, flooding and extreme temperatures (DEFRA, 2006). A good example of a case where both the efforts of public and private parties are needed is adaptation to low water levels in the inland waterway sector. Governmental adaptation measures could focus on getting rid of specific bottlenecks, e.g. building locks or dredging at locations where water levels are lowest during periods of drought (e.g. Van Leeuwen, Koetse, Koomen, & Rietveld, 2008), while the use of smaller vessels by transporters and keeping bigger stocks by shippers are potentially effective private sector adaptation measures (e.g. Jonkeren, 2010).

4. **Optimal Adaptation, Mitigation and Residual Damages from an Economic Perspective**

To make transport infrastructures less vulnerable to future climatic changes various adaptation options exist. Subsequent questions are then which option(s) to choose and how much to invest. To a certain extent these questions cannot be answered without taking into account mitigation efforts and residual climate change damages. From an economic perspective, the optimal levels of mitigation and adaptation depend on their respective costs and benefits. More specifically,

the mix of mitigation and adaptation measures should be such that damage reduction can be achieved at lowest possible marginal social costs. Given that mitigation reduces the level of climatic change, which in turn reduces damages and adaptation measures needed, there clearly is a trade-off between mitigation on the one hand and adaptation and residual damages on the other (see also Klein & Huq, 2007). Below we show how optimal adaptation and mitigation efforts can be determined from an economic perspective. For this we assume for now a world without uncertainty on climate change damages and costs and benefits of mitigation and adaptation. This issue is introduced in the next section and will complicate the determination of optimal policies. The example given below is therefore meant as a frame of reference, not as an example that can be directly implemented in practice.

In a first step we derive the optimal level of adaptation given a certain level of GHG. For this we depict in Figure 1 four different cost curves for a certain level of GHG emissions, i.e. full damages without adaptation, adaptation costs, residual damages after adaptation, and the sum of the latter two.² It is likely that marginal adaptation costs increase with the level of adaptation because the most cost-effective adaptation options will take place first. For the same reason marginal residual damages are decreasing. Therefore the slope of the adaptation cost curve increases, while the slope of the damage cost curve decreases. In Figure 1 full damage costs of climate change are initially lower than adaptation costs plus residual damages. Does this mean that accepting full damages is preferable? No, it does not. The relevant question is at which point total costs of damages and adaptation are minimal, which is when marginal costs of adaptation and residual damages, with respect to the level of adaptation, are zero. This is the case when the level of adaptation is equal to A in Figure 1. At this point, adaptation costs are equal to C, costs of residual damages are equal to D, summing up to total costs B.

Although we now have a method for deriving the optimal level of adaptation effort and the related costs, we do not yet know the optimal GHG level and the associated level of mitigation effort. For this, it should be realized that the exercise in Figure 1 can be repeated for relevant GHG levels, which would result in a total

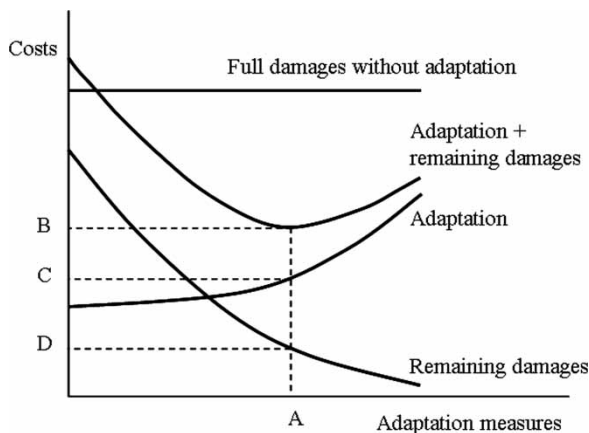


Figure 1. Full damage costs without adaptation and costs of adaptation and residual damages against the amount of adaptation effort (for a specific GHG level).

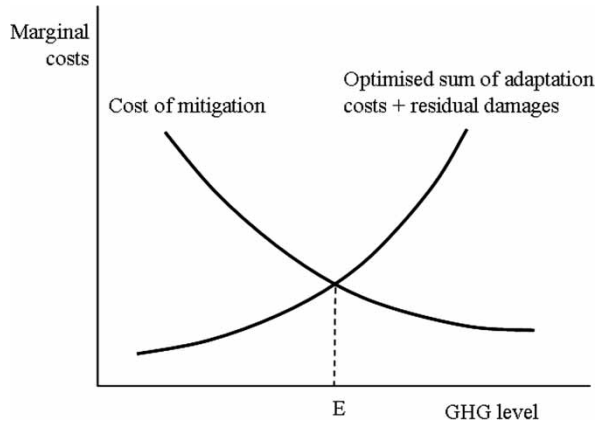


Figure 2. Marginal mitigation costs and marginal costs of adaptation and residual damages against the level of GHG concentration.

cost figure for each GHG level. These cost figures represent the optimized sum of adaptation and residual damage costs for different levels of GHG emissions, from which it is fairly straightforward to derive the marginal cost curve. This marginal cost curve is plotted against the level of GHG emissions in Figure 2, together with the marginal *mitigation* cost curve. The latter is increasing in GHG *reduction* (i.e. a downward sloping curve in terms of GHG *concentration*) because the most cost-effective mitigation measures will be undertaken first. The more GHG reduction is already achieved the more difficult and costly it becomes to reach a unit GHG reduction. The optimal GHG level is now found in point E, beyond which further abatement is inefficient from an economic social welfare perspective. At this point, the costs of reducing another unit of GHG emissions are equal to the optimized costs of adaptation and residual damages.³ The figure also clearly illustrates that optimal levels of mitigation and adaptation and damages are inter-related. For example, shifting the adaptation and damages cost curve upwards increases the optimal level of GHG reduction, and shifting the mitigation cost curve upwards reduces the optimal level of GHG reduction.

Clearly, optimal mitigation and adaptation are highly interdependent. Public sector mitigation policies are therefore suboptimal when adaptation measures are not explicitly considered in the policy mix, which unfortunately is often the case (Kane & Shogren, 2000). The rather artificial separation of mitigation and adaptation has carried over to research, so knowledge on the cross-effects of mitigation and adaptation policies is fairly limited. Some exceptions exist (see Patt et al., 2010, for an overview). For example, in De Bruin, Dellink, and Agrawala (2009a) integrated assessment models are used to balance adaptation, mitigation and residual impact damages (see also Ingham, Ma, & Ulph, 2007). The outcomes suggest that mitigation is especially relevant when optimal adaptation options are unattainable, which may be highly relevant in practice, since the consequences of climate change will likely exceed the adaptation capacity and ability of many systems in our society (Adger et al., 2007).

A certain level of climatic change has become inevitable, making the adaptation optimization problem slightly less complicated in the short run, because the interdependency between mitigation and adaptation is out of the equation (e.g. Hof, De Bruin, Dellink, den Elzen, & van Vuuren, 2010). However, additional

complexities may arise from the interdependence of different adaptation measures, especially where (infrastructure) networks are concerned (Kirshen et al., 2008). An ex-ante analysis of optimal adaptation measures may therefore be a challenge particularly in the transport sector.

One of the policy problems to achieve an appropriate balance between mitigation and adaptation is that mitigation is essentially a global theme, whereas adaptation takes place predominantly at the regional and local level. As a consequence, mitigation involves strong free rider problems so that actual mitigation efforts may well stay below the optimal level, resulting in a situation somewhere to the right of point E in Figure 2. This has two important implications. First, it induces a shift in the burden of preventing climate change at a global scale to stronger adaptation burdens in the more vulnerable regions and countries. Second, spatial spill-overs are less pronounced and less complex for adaptation than for mitigation (although adaptation spill-overs may still prove to be problematic in some cases), so free-rider problems are less problematic and adaptation is likely taken seriously by actors in vulnerable regions. As a result the distribution of climate change damages and adaptation costs is rather skewed towards more vulnerable regions, most of which are located in the global South. Therefore integrating these regional distribution effects into global mitigation negotiations may be warranted.

Although free-rider problems are less pronounced for adaptation, there still are strong reasons why adaptation efforts at the local scale may also remain below their economic optimal levels. For example, societal consequences may be unacceptable, and political agendas may be contrary to what should be done from an economic perspective. Another crucial issue is that risks and uncertainties inherent to climate change complicate the economic analysis and make it substantially more difficult to answer the question of what is appropriate and optimal adaptive action. These issues are at the heart of the next section.

5. Risk and Uncertainty

The cost curves shown in the previous section are difficult to derive in reality, mainly due to limited knowledge on climate change damage costs and costs of mitigation and adaptation. Moreover, they assume a world without risk and uncertainty, which is clearly not the case especially in the context of climate change.⁴ A formal analysis of decision-making under risk and uncertainty should play a role in any sensible economic discussion about climate change policy (e.g. Heal & Kriström, 2002). Still, in most policy documents on climatic change these issues are largely ignored. In this section we address several important topics in this area, with a focus on climate change.

5.1 Irreversibility

An important concept under risk and uncertainty is irreversibility. In the case of climate change there are two types (Heal & Kriström, 2002). First, climatic changes are themselves to a large extent irreversible. This leads to a precautionary principle, implying that climatic changes should be prevented until we know their consequences (see Moellendorf, 2011, for a short discussion). In real option terms, to be discussed in detail later on in this section, we should keep open the possibility of no climate change. A second type of irreversibility is related to the fact

that most mitigation and adaptation investments cannot be recovered once made. This leads to an inverse precautionary principle, implying that costly investments should be prevented until we are confident that they are actually needed from a social welfare perspective (or to prevent them from turning out to be insufficient or ineffective should climate change damages turn out to be larger than projected). The existence of these two types of irreversibility means that there generally is a trade-off between the risk of waiting (underinvestment) and the risk of premature action (mostly overinvestment). This is especially true for mitigation, where there is a substantial lag between changes in GHG concentration and climatic changes, also because of positive feedbacks.⁵ It holds less for adaptation, although lifetimes of many transport infrastructure investments (see TRB, 2008) are longer than the period in which climatic changes may become problematic for functioning of transport networks. The interaction between mitigation and adaptation is complex, and an analysis of optimal mitigation and adaptation under uncertainty and irreversibility even more so. To simplify matters in the remainder of this section, we focus on the current short run in which some climatic changes have become inevitable and mitigation is no longer a solution. In this case there is a trade-off between adaptation efforts and residual damages only.

5.2 Investment under Risk

In a situation where we face a trade-off between adaptation and (residual) damages two interrelated decisions have to be made, one on the magnitude and one on the timing of adaptation investment. In a situation without risk or uncertainty these decisions are fairly straightforward by using the net present value (NPV) approach. With respect to the magnitude, investment is profitable from a social welfare perspective whenever the NPV on that investment is positive. Here there is a clear relation with climate change damages, i.e. the smaller the expected damages, the smaller the level of optimal adaptation (see Section 4). With respect to timing, a general rule is that adaptation should take place now instead of later when the NPV of adaptation now is higher than the NPV of adaptation in the next period (Frankhauser et al., 1999). When risk and uncertainty are introduced, the situation becomes more complex. The underlying reason is that the NPV approach is no longer valid when the variance of possible outcomes becomes large, when outcome distributions display fat tails, when there are thresholds in the concentration-response relationship, and when there are low-probability but large-damage events (e.g. Tol, 2003; Weitzman, 2007). In the context of climate change and climate change damages these all hold to a certain extent.

Risk refers to the expected or potential losses in a situation with an unknown outcome but with known probabilities. It therefore depends on the probabilities assigned to the relevant variables and parameters. With respect to climate change and transport, damage risk can be derived as follows (TRB, 2008; RVW, 2009):

$$\text{Risk transport damages} = \text{Probability of climate change} * \text{Probability that infrastructure is affected} * \text{Damages when affected.}$$

The probabilities in the risk formula are best represented by probability distributions instead of single values, resulting in a risk distribution instead of a single risk value. In Figure 3 we give an example of such a risk distribution. Expected

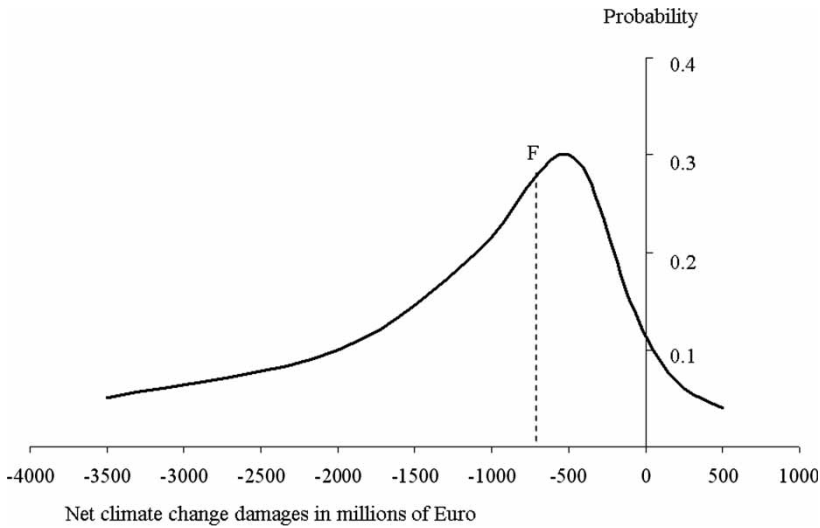


Figure 3. Example of risk distribution of climate change damages (positive damage figures imply benefits).

damages, i.e. the sum of all damages times their probabilities, are represented by point F. The median is clearly lower than that because the distribution is skewed to the left, and the probability of negative damages or benefits is substantial, as is the probability of damages that are substantially larger than the expected and median damage values. In most contemporary social cost-benefit analyses of public sector investment, risk is often neglected or is represented by a single value only (Mechler, 2003), in which case the expected value is generally used as the potential benefit of adaptation. Suppose now the NPV turns out to be positive and adaptation investment takes place, then it is clear from Figure 3 that in due time the investment turns out to have been unnecessary (overinvestment) or has been insufficient (underinvestment). Clearly, neglecting the full range of possible outcomes and using only expected values in a situation of risk is not advisable, and using risk distributions to inform decision-making is crucial for dealing effectively with climate change risk and climate change impact management (e.g. Jones, 2000, 2001).

An interesting practical application is described in Dessai and Hulme (2007). They consider several sources of risk in water resource management and apply various methods to quantify these. Ultimately, their results show risk ranges for precipitation patterns and the associated additional water required. In this particular case, the results give insight into how much additional water is required to ensure a certain level of operation and quality with 95% certainty. Although the example holds for the water supply sector, the methods used can also usefully be applied to specific adaptations in the transport sector.

5.3 Real Options and the Value of Flexibility

Although probability distributions on climate change damages are extremely useful to get insight into the risks involved in adaptation investment, they do not provide a concrete investment decision rule as an alternative to the standard NPV approach. In this respect a crucial contribution of recent economic theory is

the real options approach, which states that, for irreversible investments, risk creates an option value of waiting for more information to become available in the future. The reason is that waiting for more information reduces the probability of making an investment that appears profitable (sufficient) ex-ante, but turns out to be unprofitable (insufficient) ex-post (see the seminal work of Dixit & Pindyck, 1994). Underinvestment could be less problematic than overinvestment, simply because additional investments are always possible while disinvestment is generally not.⁶ Still, making additional investments at a later stage may be far more costly than sufficient investment earlier on, especially where transport infrastructure is concerned. In any case, applying the real options approach to climate change gives insight into whether, from an economic welfare perspective, it is optimal or not to delay adaptation investment until more information and data on climatic change and its potential damages become available in the future.⁷ Relevant here is that postponing investment becomes more attractive when the probability of change increases, in which case the opportunity costs of suboptimal investment become larger (Hobbs, Chao, & Venkatesh, 1997).

The real options approach provides an economically sound investment decision rule under risk. However, it has not been applied in practice very often. Anda, Golub, and Strukova (2009) provide an example of the real options approach for climate change mitigation.⁸ Although the situation for adaptation is slightly different, mainly because the precautionary principle of climate change prevention does not apply, the general idea is very similar. They use data from the literature as input in a Monte Carlo analysis in order to simulate distributions of costs and benefits of GHG mitigation. These distributions are subsequently used in both expected value and option value calculations. The option value is ultimately determined by relative variance, skewness and kurtosis of the cost and benefit distributions. The results show that the standard expected value approach gives a negative NPV of mitigation investment, while the option value approach gives a substantial positive NPV. Clearly, under risk the standard expected value may lead to suboptimal policy decisions.

Of course, the application of the real options approach in practice crucially depends on the availability of knowledge on the distribution of costs and benefits. Under uncertainty this information is unavailable in which case scenarios are often used to analyse the impact of alternative assumptions on cost and benefit distributions (see TRB, 2008, for an application). In actual practice using a combination of risk distributions and scenario analysis is probably needed, because probabilities may be estimated for some but not all climate developments and climate change damages. In this situation the available information on cost and benefit probabilities can be used to calculate real options for each scenario. This still has large added value above and beyond the conventional expected value or NPV approach.⁹

The real options approach has not yet made its way to the policy arena, but the option of postponement of concrete adaptation investments has been recognized in policy-related studies. For example, adaptation may involve postponing infrastructure retrofit until critical climate change parameters are known with a reasonable degree of certainty, especially when retrofit design is long-lived and wrong decisions are costly. In this case economic evaluations of costs and benefits likely indicate that it is more sensible to adapt later and accept damages when something goes wrong, rather than bearing high costs of adaptation under highly uncertain circumstances (e.g. RVW, 2009). On the other hand, it is possible that incorporating climate

change adaptation measures in scheduled retrofit, maintenance or investment can be done at little additional costs. In this case underinvestment is costly should damages turn out to be substantial, while costs of overinvestment are low should damages turn out to be limited, implying that investing now is probably sensible.

5.4 *Concluding Observations*

The economically optimal amount and optimal timing of adaptation investment is difficult to determine at the moment due to the risks associated with climate change and climate change damages. Using the real options approach, postponement is likely sensible for large adaptation investments, which does not necessarily mean that doing nothing is the best policy. Especially when adaptation in the future requires planning of long-run investment now, pro-active action is required (e.g. RVW, 2009). This requires flexibility in planning, monitoring of relevant developments, and recognition of and knowledge on existing climate thresholds. Monitoring, scientific research and development of new knowledge are crucial in this respect. The existing risks and uncertainties on climate change and climate change damages necessitate the availability of distributions and scenarios on potential costs and benefits of adaptation, and the subsequent use of option values to inform adaptation investment decisions. Uncertainty on socio-economic, technological and institutional developments is also highly relevant for developing optimal adaptation strategies (RVW, 2009).

Given the complexities involved it is not surprising that infrastructure operators and policy-makers are not used to working with distributions and scenarios, let alone that option values are an integral part of their decision-making. Investment decisions are at best informed by simple NPV calculations using expected values only, which may lead to substantial under- or overinvestment, and moreover to ineffective and potentially counterproductive adaptation measures. Clearly, incorporating risk and uncertainty into actual decision-making processes is of great societal interest. Conveying this necessity to the relevant policy arena, along with the transfer of knowledge on the available methods and tools, is therefore crucial.

6. Discussion

A growing number of contemporary policy documents are in favour of explicitly including risk and uncertainty in formulating adaptation strategies, although they may differ in the preferred method. This is an important development since it reduces the probability that valuable resources are invested in adaptation measures that may turn out to be unnecessary, insufficient or inappropriate should climate change effects be limited. On the other hand it should still be possible to (re)evaluate adaptation strategies and adaptation measures in reaction to changing insights into climatic changes and their potential damages. In this respect we advocate a rational approach to climate change and climate change adaptation, including a careful weighing of costs and benefits of adaptation and a rational approach to the associated risks. We are aware that the climate change domain is strongly politicized and media campaigns aiming at shaping risk perceptions play a strong role in several countries. This will obviously affect the way in which policies will be developed.

At the moment, given the risk associated with climatic changes and associated effects on transport, very large investments in adaptation measures are likely not

sensible from an economic perspective. This is all the more true if the negative consequences of climate change for transport turn out to be limited. Moreover, for many sectors reactive adaptation, i.e. adaptation to climate change consequences after they have occurred, is likely most efficient. Under such circumstances, and with the exception of low-cost and no-regret adaptation measures, postponing substantial investment in adaptation measures is probably a sensible strategy. In due time an increase in knowledge on physical consequences of climate change and associated effects on transport may lead to different conclusions. Further research on climatic changes and climate change damages is clearly necessary in this respect. Especially important is knowledge on weather variability, future intensity and frequency of extreme weather events, and the consequences for and vulnerability of transport networks. Also information on costs of adaptation is largely missing. These types of information and data are crucial for analysing which adaptation measures are necessary and viable from a social welfare perspective. Particularly important is research aimed at improving knowledge at the regional and local scales.

In the mean time, clever policies addressing climate problems in transport consist of three elements. First, check whether the transport networks are robust with respect to *current* weather conditions. Even when climate changes turn out to be limited, it may well be that under current conditions the system is too vulnerable. This may for example lead to additional investments in drainage for roads in the case of excessive rainfall, or additional investments in protection of switches in rail networks. Second, linkages with other policy domains may also yield opportunities for climate related measures in the transport domain. For example, linking infrastructure development to spatial planning of new residential areas or work areas may imply opportunities to design infrastructure networks in such a way that robustness is improved at low additional costs. Finally, a sensible strategy is to take low cost measures that may save large investments in the future in case climate effects in transport turn out to be severe. For example, building tunnels that are robust in case of excessive rainfall or in case of a flood may involve relatively low additional expenses. After the construction has been completed such elements are difficult to change and as a result adaptation is much more costly. This holds for other types of infrastructure as well. From a real options perspective it therefore may make perfect sense to include relatively low-cost adaptation measures in the construction or retrofit of infrastructure, because not including such measures is near irreversible or reversible only at very high cost.

Proactive or ex-ante adaptation becomes especially relevant where climate thresholds (e.g. a certain GHG level beyond which climate change is irreversible, or beyond which climatic changes suddenly increase rapidly) and large and long-run investments are concerned, because mistakes on either side may be very costly in these situations. Most elements of transport infrastructure are indeed costly and their lifetimes likely exceed the period after which climatic changes may have negative consequences. For this reason, and given the uncertainty on the magnitude of climate change transport damages, incorporating climate change in standard policies, such as periodic maintenance and investment in new infrastructure, appears to be a sensible policy strategy at the moment. Also, since spatial claims are largely irreversible, spatial reservations would enable effective responses to future climate change developments. Especially in densely populated areas, this could be an essential element of pro-active adaptation strategies at relatively limited costs.

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Notes

1. An overview of possible mitigation measures in the transport sector is provided in Chapman (2007).
2. Damage costs will occur later in time than adaptation costs, implying that a discount factor will have to be applied to make the two cost figures comparable. Without loss of generality we assume in this example that discounting has taken place and that costs hold for the same year.
3. Note that equality of marginal mitigation costs of marginal costs of adaptation and damages in point E, does not mean that mitigation and adaptation and damage costs are equal in this point.
4. Risk and uncertainty are terms that may have several meanings, and in most studies it is not always clear which. We follow the definitions originally used by Knight (1921). Situations with risk are those where outcomes are unknown but probability distributions on outcomes are known. Situations with uncertainty are those where both outcomes and probability distributions on outcomes are unknown.
5. In the literature the lag between GHG concentration and climatic changes is often referred to as the climate change commitment, i.e. the global warming that would occur if concentrations were kept at the year 2000 levels (e.g. Wigley, 2005). See Van Vuuren et al. (2008) for a discussion on why current estimates of climate change commitment are likely conservative.
6. One might also argue that lack of timely adaptation reduces traffic safety leading to more casualties. Although this appears to be an irreversibility, this is not entirely convincing from an economics perspective. The point is that what is valued in the economic approach is essentially not the life of a specific person, but the change in probability for residents to be affected by an accident (De Blaeij, Florax, Rietveld, & Verhoef, 2003). So what is valued is not life as such, but a change in risk level, which makes the notion of irreversibility less applicable since the costs of adaptation to return to the initial risk level are probably not extremely large. Note that it is not uncommon that travellers trade-off differences in risk levels against differences in costs (for example a flight with an expensive but reliable airline versus a flight with a cheap airline with unknown safety reputation). It is exactly on such private trade-offs of consumers that the valuation of risks in social cost benefit analysis of measures to deal with climate change is based. The use of a value of statistical life (VOSL) is standard in cost benefit analysis of measures that affect safety in transport, not just in the context of adaptation. As explained by Van Wee (2011), the use of VOSL to address risks in transport is consistent with some ethical theories, though not all of them.
7. Climate change may remain, at least to a certain extent, unpredictable, especially when long prediction horizons are used. For adaptation this is, however, less likely and also less problematic than for mitigation. In the extreme case that waiting does not solve the decision problem about adaptation investment there is always the option of waiting until actual climatic changes are revealed before making investment decisions.
8. Various software packages are available that allow for calculating real option values. For example, Anda et al. (2009) use the software package *Real Option Analysis Toolkit 2.1*.
9. For other interesting approaches to deal with uncertainty and the timing of adaptation investment, see Peterson (2006), Mastrandrea and Schneider (2004), Hobbs (1997), Hobbs et al. (1997), and Gu, Crawford, Peiris, and Jefferies (1994).

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