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ADAPTATION TO CLIMATE CHANGE
IN THE TRANSPORT SECTOR:
A REVIEW

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Abstract

The paper identifies the literature that deals with adaptation to climate change in the transport sector by means of an extensive search, and presents a systematic review of the publications. Although it is frequently claimed that this socially and economically important sector is particularly vulnerable to climate change, there is comparatively little research into adaptation by industry, utilities and settlements. The 63 sources we found are analysed following an action theory of adaptation that distinguishes different adaptational functions. A very heterogeneous set of adaptations is identified and the actors and means of adaptation are classified by an open coding procedure. The paper shows that a broad diversity of actors is relevant for adaptation in the transport sector – ranging from transportation service providers to public and private sector actors and private households. Most adaptations discussed in the literature require inputs in the form of technical means, institutional means, and knowledge. The review shows that the existing literature either focuses on overly general and vague proposals, or on detailed technical measures. The paper concludes that the knowledge on adapting transport to climate change is still in a stage of infancy and suggests fields for further research.

1 Introduction

The transport sector fulfils crucial economic and social functions. Other sectors as well as society as a whole are dependent on a well-functioning transport sector. Since many transport services strongly depend on weather conditions, it is important to understand if and how these services should be adapted to current and predicted future climate change. This paper provides a general overview of the current situation. First, we identify the literature on adapting transport to climate change. Second, we group and systematize proposed adaptations and those already being made, as described in the literature. Third, we identify the actors that are involved in adapting the transport sector to climate change. This analysis of actors and means for adaptation provides a detailed picture of adaptation that, if generalized, is likely to hold for further sectors.

There are few systematic studies of adaptation by the transport sector to the impacts of climate change, except of a medium-sized set of case studies (see this review). Compared to the voluminous research into the effects of climate change on ecosystems, there is very little on the adaptation that will be required by industry, settlements and society (IPCC, 2007) or changes that will need to be made to the built environment (Arnell, 2010). This is despite the claim that the transport sector is particularly vulnerable to climate change (e.g. Eddowes et al., 2003, IPCC, 2007, Savonis et al., 2008). Transport infrastructure is affected by extreme weather (e.g. flooding of roads and railways, threats to passenger safety during heat waves, delays due to storms), and by continuous climate change (e.g. permafrost melting under roads in the arctic, concrete degradation). Transport delays and interruptions have high social costs. The ability of the transport sector to respond rapidly to climate change is constrained by its reliance on long-lasting infrastructure (e.g. bridges, tunnels, railway lines, roads, airports, seaports; see Stecker et al., 2011, for an assessment of infrastructure lifetimes). Therefore, anticipatory adaptation is needed. Furthermore, spatial development plans can not be revised at short notice, and transport infrastructure and services are often highly regulated. Thus timely adaptation of the wider institutional environment will also be required. In an extensive review

of the adaptation literature in the Climatic Change Journal, Arnell-2010 shows that the majority of contributions are primarily concerned with determining impacts, and less with adaptation measures and decisions. There is a need to focus more on adaptation and not just on impact and vulnerability assessments. Finally, the transport sector exemplifies the wide diversity of actors that are typically involved in adaptation (cf. Schwedes, 2011). Although it is recognized that an actor-oriented focus is generally essential for the study of adaptation, since it is “concerned with actors, actions and agency” (Nelson et al., 2007, p. 398), this approach has not been extensively applied in the theoretical literature on adaptation to climate change. Likewise, the analysis of interlinkages between the means and ends of adaptive action has considerable potential but, to our knowledge, has been touched on only briefly by Bohle (2001) and Jetzkowitz (2007) (see Eisenack and Stecker, 2010, Eisenack, 2011, for a more detailed theoretical study). Because of the multitude of actors involved (Klein et al., 2005, Eisenack et al., 2007, Reckien et al., 2009), developing strategies to support or enable adaptation seems difficult. This holds particularly true for the transport sector, where private requests for mobility, economic interests of transport providers, and concerns about the wider public good have to be harmonized. This complexity may partially explain missing action for adaptation. To address adaptation in the transport sector, the types of problems and opportunities relevant to the different actors involved have to be carefully and systematically disentangled.

We review papers from 22 scientific journals (years 2005-2009) and other sources that explicitly address adaptation to climate change in the transport sector. We looked for other contributions in a further 66 journals, but with negative results¹. The adaptations mentioned or discussed in these texts are grouped and coded following a modified Grounded Theory procedure. This is structured along the lines of an action theory of adaptation (see Eisenack and Stecker, 2010), that is outlined below. It is especially designed to capture the actors and resources involved in adaptation. Within the scope of this paper, we consequently put emphasis on the actor and action oriented aspects of the adaptations we found in the literature.

The review concludes that the literature on adapting transport to climate change is indeed thin on the ground and scattered among a broad set of journals and authors. Nearly all modes of transport are addressed, but with an emphasis on road and water transport, and much less on rail and air transport. There is a gap between overly unspecific adaptation proposals on the one hand, and very detailed, often technical adaptation measures on the other. Although there are also proposals for more practice-oriented and institutional adaptations that would be helpful for decision-makers, these are mostly found in the grey literature. Many proposed adaptations follow a “top-down” scheme where a public actor is charged with enabling or obliging a transport provider to adapt with the ultimate goal of reducing risks for transport users.

We now outline our theoretical base and then describe the methodology used to select and code the documents. After presenting our results, some more general conclusions follow.

¹ The list can be obtained from the authors upon request.

2 Theory and Methods

2.1 An Action Theory of Adaptation

To review and analyze the observed and proposed adaptation measures in the transport sector we need to operationalize the concept of adaptation we use. A systematic representation is vital for comparing adaptations and provides the basis for identifying well-researched aspects in adaptation, gaps in the literature, and potential barriers to adaptation. Adaptation of crucial socio-economic sectors such as transportation involves conscious social action and therefore excludes some forms of autonomous or reactive adaptation. However, the actors and their actions and intentions are seldom analyzed systematically in contemporary adaptation literature, even though the question “who or what adapts?” (Smit et al., 2000) is a cornerstone of adaptation research. This calls for a systematic reanalysis of who, where and how different actors are or can be involved in adapting transportation. For this purpose we now outline our action theory of adaptation (see Eisenack and Stecker, 2010, for a more extensive presentation and discussion).

In analytical philosophy, action is defined to be an act, exercised by an actor with an intention (e.g., Wilson, 2008). We adopt a terminology which is partially rooted in the established “action frame of reference” (Parsons, 1937), and apply it to the actions of the transport sector in response to climate change. Parsons (1937) analyses action with reference to the actor, the means and ends of the action, and some further aspects. Accordingly, we distinguish between the actors, the purpose or target of an action, and the act itself. In our action theory of adaptation, the actual or potential impact of climatic changes, i.e. shifts in biophysical and particularly meteorological variables, on a given system such as transportation, is understood as a *stimulus* for adaptation. These changes affect an *exposure unit*, i.e. one or more actors, or a social or non-human system, and motivate adaptation. When considering human actors we generally distinguish between individuals, collectives of individuals and organizations (e.g. companies and public bodies). An *operator* is an individual or collective actor that takes action whose purpose is adaptation. To this end, *means* (e.g. resources, information etc.) are required that the operator employs to achieve the intended ends. These ends are associated with (other) actors, and social and non-human systems, called *receptors* of an adaptation. The receptor can be the exposure unit, but may also be different from it. Fig. 1 illustrates the theory.

As an example, consider public information provision about risky travel behavior with respect to heavy rain. Although information provision is not a specific adaptation that, in itself, makes travelling less risky, it may facilitate specific adaptations, e.g. by individuals through behavioral and modal changes. Information provision as an adaptation measure may be motivated by actual or expected increasing frequency and strength of precipitation events, which represents the stimulus. The exposure units are users of transportation and transport providers. The operator is a public body that collects and provides the information, with the latter being the means of the action. The intended end is to change behavior of transport users, making them the receptors. Here, the receptors are a subset of the exposure units (transport providers are exposure units not addressed by this adaptation).

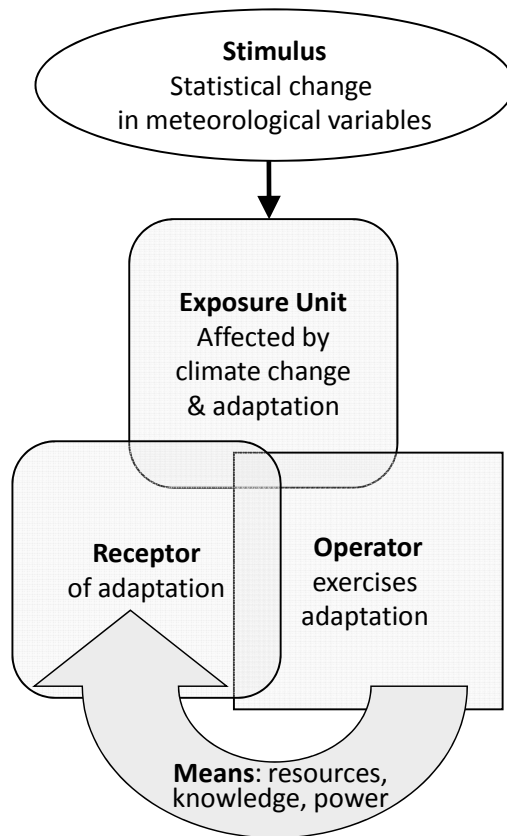


Figure 1: Schematic illustration of the core concepts of the action theory of adaptation. Boxes with rounded corners can be both actors or biophysical units, while operators are always actors. The three adaptational functions (operator, receptor, exposure unit) may or may not overlap. Depending on the boundaries of analysis, an actor or unit may assume only one or multiple adaptational functions. The simple arrow denotes a causal nexus, and a thick one a teleological nexus.

This example shows that an actor can be a receptor in one adaptation, but an operator in another. Also, biophysical units (e.g. technical devices, protective structures) can be both exposure units of climate stimuli and receptors of adaptations. In our terminology, the place that is occupied in the schema (as operator, receptor or exposure unit) is denoted the *adaptational function* of an actor or a biophysical unit. Depending on adaptation under consideration, an actor can have different adaptational functions.

From the standpoint of this theory, we can define what we consider to be an adaptation to climate change in this review as follows. Adaptations are social response by individuals, sets of individuals or organizations in the broadest sense, directly or indirectly intended to change the way exposure units are affected by stimuli arising from climate change.

2.2 Document Selection

This review is based on an extensive body of scientific literature consisting of peer reviewed papers, contributions to scientific books, government or government commissioned studies (national and sub-national level), and technical reports (cited in IPCC, 2007). We selected contributions that:

- deal with the issue of climate change,
- focus on or contain sections on transportation and transport infrastructure, and
- explicitly consider adaptation to climate change. (This criterion means that publications that discuss measures to reduce greenhouse gas emissions or ways to deal with governmental mitigation policies, but without explicitly considering adaptation are excluded.)

Document selection started with the compilation of a list of 88 journals in the relevant scientific disciplines of (1) economics, political science, geography, spatial planning, and modeling (insofar as they consider climate, environment and sustainability), (2) transportation, disaster studies, planning, law and engineering, and (3) climate change, the environment and sustainability science. The journal list was drawn up based on interviews with experts from climate change research, environmental economics, spatial planning, urban geography, disaster risk reduction and the authors' own expertise. It was augmented by an internet search for peer-reviewed journals in the respective disciplines, citations in previously identified literature, and the journals referenced in 'Chapter 7: Industry, settlement, and society' of the Contribution of Working Group II to the 4th Assessment Report of the IPCC (IPCC, 2007). We carried out a full text search for key words in these journals for the years 2005 to 2009. For the journals mentioned under (1) and (2), articles that use the keyword "climate change" or "global warming" were selected; in the journals that primarily deal with climate change or sustainability issues listed under (3), the keyword "transport" or "infrastructure" was used. By selecting the journals with at least one contribution found by the keywords, a refined list of 22 journals was obtained (see Tab. 1).

Documents were selected by inspecting the table of contents of the identified journals between 2005 and 2009. By reading the abstracts and inspecting the whole papers, we discarded all articles that did not address adaptation at least to some extent. Non peer-reviewed sources were included if they were referenced in Chapter 7 of the Contribution of Working Group II to the 4th Assessment Report of the IPCC or in the settlements, industry, society and infrastructure-related sections in the regional chapters (IPCC, 2007). Our collection of documents was finalized by means of an internet-based desktop review of relevant scientific books, institutions and reports, in particular those that were referenced in the previously identified literature. Only studies undertaken or commissioned by public authorities, working papers of scientific institutions and contributions to scientific books were considered. If those documents or those cited in the IPCC were published before 2005, they are nevertheless included in the review if they are cited in the other retrieved literature very frequently.

2.3 Coding of Adaptations

From the selected documents we extract all sections that describe adaptations. Each adaptation is summarized in a short description, identifying, where possible, the operator, the receptor and the exposure unit. This structure is further refined applying an open coding procedure that follows the principles of Grounded Theory (Strauss & Corbin, 1998). According to Grounded Theory, open coding refers to the process of assigning concepts (the codes) to parts of a text (here: the descriptions of actors and adaptations). The set of codes that is used for assignment is developed at the same time as reading the text, so that the codes used adequately represent the text corpus. Thus, both the complete code system and the classification of adaptations by codes emerge from the text. Original Grounded Theory nevertheless follows a basic theoretical scheme of human behavior (e.g. by

requiring codes for conditions, strategies and consequences). In our modified procedure, the action theory of adaptation assumes this role. Since some types of actors, social and bio-physical units appear both as receptor and exposure unit, they are classified using the same categories, e.g. as rail and road infrastructure, or as public and private actors. The same code is attached to every actor or system of the same type. If necessary, the developing coding system acquires a hierarchical structure with sub-concepts, e.g. with transport users as sub-category of private actors. The coding of actors is based on explicit statements about their roles in the documents. If not explicitly available, we code the actors based on our interpretation, but only if this is fairly straightforward to do. Otherwise, the adaptations are not completely coded with respect to the adaptational functions. The coding procedure continues until the coding system captures the multiple facets of the identified adaptation and shows a balanced and consistent conceptual structure. The resulting coding system is presented below in the results section.

In addition to coding actors, we determine which modes of transport (rail, car, etc.) are addressed. This is not possible for all adaptations, since this is not always specified, and some adaptations are more general or apply to multiple modes. Finally, the adaptations are classified by the means that they employ (if this could be identified from the text). This is required to identify the types of resources that are or will be explicitly or implicitly needed to implement the adaptation. As far as possible, we stick to the means that are explicitly mentioned in the article. The resulting codes for means are presented below as well.

The final code system, being informative in its own right, can further be used for quantitative analysis, for example to analyze how frequently different actor types occur as operator, receptor, and exposure unit. Commonly occurring “constellations”, i.e. recurring patterns of assignment of actor types to adaptational functions, can be identified. The frequency of different modes of transportation and means employed can be measured as well. We want to emphasize however that the frequency of specific actors and modes of transport in the texts does not say anything about whether they are indeed frequent or crucial for adaptation to climate change. In contrast, the procedure is particularly strong to yield classifications that represent the *diversity* of adaptations that appear in the literature.

3 Results

3.1 Identified Documents

In the 5-year time period yielded a total of 35 articles in 22 peer-reviewed journals that address adaptation to climate change in the transport sector. The journals ‘Journal of Transport Geography’, ‘Natural Hazards’, ‘Routes/Roads’, ‘Water Science Technology’ published three articles each, which is the most numerous across all journals. The remaining 23 articles are taken from 18 other periodicals. The full list of papers is given in Table 1. In addition to the journal papers, we identified 28 contributions in book chapters, from scientific institutions or government organizations. This gives a total of 63 sources.

Table 1: Contributions in 2005-2009 by journal. In contributions with an (*) adaptations are identified for coding.

Ambio	Prowse et al. (2009)*
Canadian Water Resources Journal	Millerd (2005); Sung et al. (2006)
Civil Engineering-ASCE	Brown et al., 2005
Climatic Change	Kirshen et al. (2008a)*; Kirshen et al. (2008b)*
Ecological Economics	Grazi & van den Bergh (2008)*
Environment and Urbanization	Roberts (2008)*
Geneva Papers on Risk and Insurance	Mills (2009)*
Journal of Climate	Hanesiak & Wang (2005)
Journal of Cold Regions Engineering	Cheng (2005); Alfaro et al. (2009)*
Journal of Infrastructure Systems	Cai et al. (2007)*; Chinowsky et al. (2009)*
Journal of Sustainable Transportation	Black & Sato (2007)*
Journal of Transport Economics and Policy	Jonkeren et al. (2007)*
Journal of Transport Geography	Jenelius (2009)*; Andrey (2009)*; Marsden & Rye (2009)
Land Economics	Botzen & van den Bergh (2009)*
Municipal Engineer	Arkell & Darch (2006)*
Natural Hazards	Kleinosky et al. (2007)*; Birkmann et al. (2009)*; Sheng & Wilson (2009)
Ocean Development and International Law	Pharand (2007)*
Raumforschung und Raumordnung	Birkmann & Fleischhauer (2009)*
Routes/Roads	Grondin et al. (2005); Parriaux (2008)*; Savard & Musy (2008)*
Transport Policy	Da Silva et al. (2008)
Transportation Research Part D	Suarez et al. (2005)*; Koetse & Rietveld (2009)*
Water Science Technology	He et al. (2006); Arnbjerg-Nielsen & Fleischer (2009)*; (Wesselink et al., 2009)*

Adaptation by the transport sector to climate change is an increasingly discussed topic in the scientific literature. There is an upward trend in the number of publications per year during the period (see Tab. 2). With respect to author- and co-authorship, and giving equal weights per selected article, there are many contributors who are represented once. Only six authors are mentioned more than once in the peer-reviewed sources (see Tab. 3).

Table 2: Number of identified publications in peer-reviewed journals by year.

	Year				
	2005	2006	2007	2008	2009
Number of publications	6	3	5	7	14

Table 3: List of 'frequent' authors in peer-reviewed journals (no weighting of author position).

(Co-)author of two papers	Anderson, W.; van den Bergh, J.C.J.M.; Birkmann, J.; Kirshen, P.; Rietveld, P.; Ruth, M.
(Co-)author of one paper	80 further persons

3.2 Identified Adaptations

Altogether we identified 245 adaptations from 25 peer-reviewed papers and 25 contributions in the grey literature. More than half of the adaptations analyzed in this review (about 60%) are described or proposed in the grey literature (in particular studies commissioned by public bodies), that comprises only about 45% of the reviewed texts. Many publications just discuss a small numbers of adaptations, but some are very extensive (in particular in the grey literature: Savonis et al., 2008, TRB, 2008, Cochran, 2009, PIARC, 2008, Zimmerman, 2002, Mayor of London, 2005; in the peer-reviewed literature: Kirshen et al., 2008a, Kirshen et al., 2008b, Prowse et al., 2009, Pharand, 2008).

The mode of transport to which an adaptation applied was coded by assigning it to one of the following categories: *air*, *water*, *rail*, *road*, and *others*. A noticeably large number of adaptations (about 40%) fell into the last category. In a few cases these related to modes of transport not covered by the other categories (e.g. pipelines), but in most cases this code was applied to adaptations that addressed “transport infrastructure” or “critical infrastructure” in a very general sense, and so could not be assigned to a distinct transportation mode. A further 28% of the adaptations relate to road transport, 21% to water, 9% to rail, and merely 2% to air traffic.

For coding “means”, we identified four categories: *technical*, *institutional*, *knowledge* and *others*. The following paragraphs define and analyze these categories, and illustrate them with examples.

Institutional means encompass institutions set up by governments or public sector agencies, standards for technologies, and public and private sector frameworks for investment and planning decisions. *Institutional* means account for the largest group of all identified adaptations (43%). Within this group, the sub-category *planning* accounts for almost two thirds of the means. The adaptations described are often rather general (e.g. “formation of new institutional and contractual relationships”, “moving or protection of roads” or “using operational procedures [...] for infrastructure services [...] to reduce or avoid population exposure during hazard events”). Likewise, there are general references to relocation of existing infrastructure or redesigning structures as means of adaptation. Very much in contrast, we also found very specific suggestions for the revision of land-use regulations. The remainder of this category falls under *water management*, a specific issues that accounts for a remarkable share of the total. All in all, adaptations covered by this group of means include both very general and some quite specific proposals.

The *technical* category covers concrete measures such as “air conditioning of vehicles”. This category does not include decisional procedures and standards for technical measures (they are coded as *institutional*). This is the second largest category of means (33%). As might be expected, means in this category are predominantly explicit and concrete recommendations as in the above example. Other included: “modifying the design of the fill and soil compaction when using excessively dry materials in the construction of roads”, or “use of granular protection against erosion”.

In contrast, the *knowledge* category (14%) comprises rather general adaptations such as “education and training of professionals”, “facilitating understanding of climate change in management”, and “creating databases of public infrastructure”. This category groups all adaptations that focus on science, research, information and communication, as well as monitoring and information gathering systems. “Estimating risks and assessing consequences of climate change before starting new projects”, or “ranking identified risks” and “developing action plans to manage prioritized risks” are examples of means in this category. Within the category, 33% of all means were assigned to the sub-category *monitoring*.

The category *others* is a residual one (10%). In the literature we found some rather generic but unspecific principles for adaptation (e.g. “flexible / adaptable designs”). Financial and insurance instruments, investment financing, shifts from one mode of transport to another, and behavioral changes of individuals were also coded as *other means*.

We now turn to the actors and adaptational functions of actors and non-human entities. This is a key part of the analysis. Many actors fulfill multiple functions, for example as receptor or exposure unit as well as operator. Likewise, the same biophysical unit can be both a receptor and an exposure unit. As mentioned above, for this reason we started out by assigning categories to actors regardless of their adaptational function. In other words, we first introduce the categories and then show how they assume different adaptational functions.

For non-human entities we simply use the category *biophysical*, and do not go deeper into subcategories. For actors, four main categories are identified. These are further divided into subcategories that also illustrate the definition of the categories. (Numbers in brackets indicate the frequency of occurrence of the actor type as a percentage of all coded actors, irrespective of whether they appear in the adaptational function of operator, receptor or exposure unit.)

- *Transport* (33%): Individuals or organizations that run transport systems. Important subcategories include *infrastructure providers*, i.e. organizations that own, manage or maintain basic fixed transport assets such as roads, railway lines and airports; and *transport operators* that dispose of more flexible assets as ships, trucks or buses. We do not distinguish between public and private *transport operators* and *infrastructure providers*, as this cannot be inferred from the literature in most cases. Such a distinction would also depend on the institutional context of an adaptation, in particular the ownership model for a transport system. The third sub-category is *transport staff and management*, i.e. groupings of individual actors, who are the focus of interest of a number of publications. It was of no further use to distinguish between *transport staff of infrastructure providers* and *transport operators*.
- *Public* (25%): Actors from politics, public administration and publicly funded organizations, apart from public sector providers of transportation and infrastructure, which are considered part of the *transport* category. The subcategory most frequently referred to is *public sector agencies*, i.e. administrative bodies in the public sector across all institutional scales that are more or less independent of national governments. Key agencies in this subcategory are those responsible for urban and spatial planning, water management and transport regulation. Another, less frequently mentioned but still important subcategory is *government bodies*, including national, regional or local government structures, for example ministries of

transport. Other categories include *knowledge organizations* (universities, research institutes, professional education institutions), and *public sector staff and management*.

- *Business* (19%): Private enterprises, apart from private providers of transportation and infrastructure that are part of the *transport* category. These are very diverse (e.g. manufacturing and mining), but the sectors *logistics* and *finance* (in particular insurance) appear quite frequently in the literature. Another subcategory is represented by *users of energy technology and temperature sensitive buildings*. Again, *business staff and management* is a final (small) subcategory.
- *Household* (24%): Private actors, individuals and member of the general public, as consumers or property owners (in contrast to private enterprises). The most prominent subcategory is (as might have been expected) *transport users*. However, *residents and private property owners* are considered as well.

We now investigate which actors appear in which adaptational functions, and start with the operator. The categories which most frequently appear as operators are *transport* (accounting for 49% of operators) and *public* (37%). *Households* are hardly represented as operators. There are more *business* operators, but they are scattered and of very diverse types. However, *logistics* and *finance* account for roughly one half of the *business* operators.

We now turn to the receptors, where all actor types can be found (*transport* 16%, *public* 14%, *business* 27%, *household* 27%), but also *biophysical* units (16%). In this respect, this is the most diverse adaptational function in the literature on the transport sector. Compared to the operators there is slightly more representation of *business* and *household* actors (see next section of a more detailed analysis of this observation). When, subcategories are further investigated, the diverse picture mostly remains. However, *finance* almost never appears as receptor, and *infrastructure providers* are targeted roughly twice as frequently as *transport operators*. *Public sector agencies* appear much less frequently as receptors than as operators.

For exposure units, in contrast, the picture is much clearer. More than a half are *biophysical* units, and *households* make up more than a quarter. The latter are mostly *transport users*, but *residents and private property owners* appear more frequently as exposure units than as operators or receptors. *Public* and *transport* actors are very infrequently identified as exposure users (with *infrastructure providers* accounting for the largest number of instances). Exposed *business* actors (8%) are the *users of energy technology and temperature sensitive buildings*, while the *finance* sector was not mentioned once as an exposure unit.

Up to now, we have investigated the distribution of adaptational functions among actors. It is also interesting to consider how frequently the different actor types assume each of the adaptational functions. *Public* actors mostly appear as operators (73%) or as receptors (21%), but not very frequent as exposure units. *Government bodies* and *public sector agencies* do not occur as exposure units. The picture is similar for the *transport* actors that predominately have the adaptational function of an operator (73%) and only occasionally appear as receptors (19%). This is unexpected, since *transport operators* and *infrastructure providers* might have been seen as those that are most likely affected by climate change (i.e. as exposure unit). *Transport staff and management* account for about one third of the operators in the *transport* category. Interestingly, *business* actors appear in all three adaptational functions, but primarily as receptors (53%). Within this category operators are

found slightly more frequently in the sectors *logistics* and *finance*, while *users of energy technology* and *temperature sensitive buildings* are rather more likely to appear as exposure units. *Household* actors appear as exposure units (51%) and receptors (42%). Both *transport users* and *residents and private property owners* occur as exposure units, but *transport users* more frequently as receptors. *Households* are almost never seen as operators, the exceptions relating to adaptations involved changes in behavior or shifts between modes of transportation (modal split).

3.3 Further Observations

The coding of actors in the transport sector shows that it is not sufficient just to classify by three categories of *public*, *business* and *household*. There is a remarkable number of “hybrid” actors that cannot always assigned to the public or the private sphere in a clear-cut way (e.g. transport operator and/or infrastructure operator). Therefore the further category *transport* needs to be added. This is not particularly due to our specific focus on transportation, but due to the specific conditions of this sector. It should be further noted, that private transport actors are often strongly regulated by public actors. We conclude that a separation between the public and the private sphere is, similar to other utilities but different from other sectors, particularly difficult in the transport sector.

In general we observe that it was easiest to identify the operator of an adaptation; the receptor was also generally easy to identify. Except for *transport users* it was more difficult to identify the exposure unit. For 81% of the adaptations it is possible to name the operator, in 42% of all cases the receptor could be identified, and in only about 33% of cases the exposure unit. The literature frequently discusses adaptations without being so explicit about the impacts from climate change they are targeted at.

It is a striking result that there appears to be a gap in the literature between overly unspecific and vague guidelines for adaptation (e.g. “relocation of vital assets”) and very specific and concrete adaptations (e.g. “air conditioning in vehicles”, “use of continuous welded rail lines”). Most of the very specific adaptations use *technical* means or *standards* as *institutional* means. Other *institutional* means are mostly unspecific, together with *knowledge* means (e.g. “emphasize the need of adaptation measures within all sectors”, “education of ship crews for arctic trade”). *Planning* is a key subcategory of *institutional* means where many vague recommendations can be found (e.g. “appropriate zoning and transportation planning”). The question is whether there are crucial adaptations in between unspecific and overly detailed adaptations. Those would be institutions or instruments that are general enough that they, on the one hand, do not require detailed technological or local knowledge. They can be centrally defined rules, and they can be applied to different contexts. On the other hand, they should be sufficiently specific that they indeed shape decision making for adaptation. Many *planning* means have the potential to be spelled out more concretely (e.g. “review of cost-benefit decision-making exercises used in infrastructure choice”, “Anpassung der Verkehrsplanung: Planfeststellungsverfahren §§ 72-78 VwVfG“ German Administrative Procedures Act).

We finally investigate typical combinations of actor types and biophysical units in the different adaptational functions. Since there are many adaptations where not all three functions can be identified, we do not present a quantitative assessment. Nearly all possible combinations occur, but with very different frequencies. There are only a very limited number of adaptations where the operator is of the type *household* or *business*, and the receptor is of type *public* or *transport*. We may

say that this research gap demonstrates a lack of interest in bottom-up adaptational function constellations. In contrast, there are two adaptation types that occur quite frequently: those with a top-down pattern, and those that are primarily technical. (1) A typical top-down pattern of adaptational functions has a *public* operator, a *transport* receptor and a *household* or *biophysical* exposure unit. Another frequent top-down pattern has a *public* operator, a *business* receptor (usually as a transport user) and a *business* or *biophysical* exposure unit. When both receptor and exposure unit are *business*, usually technical means are considered. (2) Another frequent, less top-down pattern are adaptations with *transport* operators, where receptors and exposure units are frequently *transport* actors as well, or else *biophysical* units. These adaptations make up a large fraction of those with *technical* means. We thus may summarize the current literature is focusing either on technical solutions or on public sector responsibility for adaptation.

4 Conclusions

This paper reviews the literature that explicitly considers adaptation to climate change in the transport sector. A broad diversity of 245 adaptations is identified in 63 contributing sources over 5 years from 2005-2009 (including some important texts published before 2005). The actors and means of adaptation are classified using an open coding procedure that builds on the action theory of adaptation (Eisenack and Reckien, 2010). It appears that this theory is particularly useful for systematizing the differences between adaptations and disentangling the complex actor networks involved in adapting the transport sector to climate change (see Reckien et al., 2008, for a further discussion). It is hence useful in guiding research on adaptation and may help to identify relevant institutional structures for the practical development of adaptations.

We generally find that research on adapting transport to climate change is in a stage of infancy. Although we also find multiple vulnerability studies that may support adaptation of the transport sector (not included in this review), there is little work that explicitly addresses adaptation. This is in line with other observations of the state of the art in adaptation research (Arnell, 2010). Contributions are scattered over a wide range of sources and authors. There are no dominant journals or researchers. Much knowledge on adaptation in this field has not appeared in the peer-reviewed arena yet (e.g. TRB, 2008, Cochran, 2009). Many proposed adaptations are only very general guiding principles (“protection in high density developed areas”), and do not address specific modes of transport. The majority of the more specific adaptations are technical and address road and water transport.

The sources mostly suggest adaptations without discussing how they should be implemented. They hence do not address the factors that would support and constrain the implementation of the adaptations. Research on supporting and constraining factors is vital for improving the feasibility of suggested measures and for analyzing how different actors could cooperate in the development of adaptations. However, this would require a clear understanding of the different actors and their adaptational functions. If adaptation to climate change were at a more advanced stage, knowledge of relevant means of action and on actor relations would be more detailed. This is illustrated by the research gap between concrete technical adaptation measures, and very vague or general principles of adaptation. Both types are limited approaches: vague principles of adaptation do not provide the necessary advice to guide actors in planning adaptation. Detailed and concrete technical adaptations on the other hand may be too context-specific to be transferred to and replicated by other actors.

There is thus a need for research on more precise institutional rules or instruments ('adaptation instruments') that should be as generic as possible in order to facilitate the concrete organizational or technical measures required. Such proposals (e.g., from our study, „apply a safety factor for choosing the size of the drainage system to prepare structures for increases in runoff water“, „tighter federal disaster relief aid“, „establish a Department for Arctic Affairs to coordinate internal and external cooperation“) could provide the starting point for the definition of rules, responsibilities and incentives for the decisions that are necessary to adapt to climate change. Adaptation instruments of this kind are especially applicable to the top-down pattern of adaptation we often find in the literature: a public operator may set a regulatory frame that provides guidance but leaves enough space for receptors to make use of their context-specific knowledge in order to develop their own concrete adaptations.

In this respect it is crucial to clarify the role of the public sector in adaptation (cf. Dannenberg et al., 2010). While some economists argue that most adaptation should be led by the private sector (e.g. Nordhaus, 1990), many articles in our review envisage a strong role for the public sector as operator, which (indirectly) supports private transport users as main exposure units. The role of the public sector in promoting adaptation in the transport sector is also underpinned by the fact that key actors in this sector, in particular transport operators and infrastructure providers, often have a hybrid status in terms of private/public ownership or discretionary power. Shareholders may be public, private or a mixture of the two, and the transport sector is mostly strongly regulated. Thus, gaining an understanding of the institutions that would effectively guide adaptation to climate change in the transport sector remains a challenging but interesting and necessary endeavor.

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