

Innovations in weather services as a crucial building block for climate change adaptation in road transport

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The road transport sector is facing rising uncertainties in planning and operations due to climate change induced changes in weather variability and extreme events. However, because of the high level of uncertainty related to the future climate, adaptation measures should be robust so as to retain the option value of the portfolio of measures. As an example of such a measure, this paper evaluates how foreseen innovations in weather services could reduce weather sensitivity and, consequently reduce the negative effects of climate change in the sector. The study is based on a theoretical framework on climate change adaptation and valuation of weather and climate services using the Weather Service Chain Analysis. We apply these frameworks to the road transport sector with a special emphasis on drivers' decision making before and during a trip. We show that improved weather information, including more accurate weather forecasts, new applications and information dissemination channels can decrease the vulnerability of the mode to projected shifts in extreme weather patterns due to climate change.

Keywords: Adaptation, Climate Change, Information, Innovation, Road transport, Weather Service

1. Introduction

1.1 Climate change and the transport sector

The link between the transport sector and climate change is twofold. Mitigation of climate change, for instance the reduction of greenhouse gas emissions from transport activities, has received plenty of attention due to its significant contribution to the global emissions (IPCC, 2014a). However, the transport sector is not only a contributor to climate change, but in all likelihood will be notably affected by its consequences (Hallegatte, 2009; IPCC, 2014b; Love et al., 2010).

The report by the Intergovernmental Panel on Climate Change entitled *Impacts, Adaptation and Vulnerability* reviews the expected direct and indirect impacts of climate change on transport (IPCC, 2014b). The impacts are not uniform, and depend, for instance, on the geographic area considered, transport mode, time frame and factors such as technological development and economic growth (IPCC, 2014b; Koetse and Rietveld, 2009; Michaelides et al., 2014; Nokkala et al.,

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2012; MMM, 2012). Koetse and Rietveld (2009) suggest that the changing weather variability and extreme weather events may be the impacts of most concern for the transport sector.

Weather related disturbances, existing in the current climate, already affect the transport sector. In the aviation sector, the main weather related costs are related to both primary and network delays, cancellations and diversion (e.g. Cook et al., 2004). For road transport, weather related accident costs dominate other weather related costs (Nokkala et al., 2012). With regards to rail transport, extreme weather has an effect on operating efficiency, physical infrastructure and the safe passage of freight and people (Rossetti, 2007). For maritime transport, weather has an effect on stability, journey time, safety of the cargo and vessel, fuel efficiency and admissible load factor (Nurmi et al., 2012). Additionally, transport modes do not operate in isolation but rather constitute a multi-modal transport network, in which chain events can emerge even if adverse weather directly affects only one mode. Indirect impacts of climate change may stem from for instance changes in agricultural, tourism and production patterns (Koetse and Rietveld, 2009).

The projected effects of climate change on the frequency and intensity of extreme weather events in different regions in Europe still have a significant degree of uncertainty due to their combination with other sources of uncertainty, such as natural variability of the climate, uncertainty in climate and economic modelling and socioeconomic development. The highest level of uncertainty is related to changes in extremes. Nonetheless, with reasonable confidence it is projected that the frequency and intensity of cold waves is will decrease throughout Europe, while the duration and occurrence of heat waves is projected to increase. In particular the projected levels of extreme precipitation and wind speeds in future climates entail higher uncertainty as compared to temperature. Jylhä et al. (2009), nonetheless, find that in northern Europe, extreme downpours may be expected to increase. In principle, extreme winter-weather events (cold spells, blizzards and snowfall) are expected to decrease in most regions of Europe by 2050; an exception is that the frequency of extreme snow storms is projected to slightly increase in Northern Europe. (Vajda et al., 2011; Perkins et al., 2012). In a study on the Alpine region, Rajzak et al. (2013) project that in several areas of the northern Alpine region, the severity of extreme precipitation (snow) in winter time increases, while the frequency might decrease. In other seasons, the tendency is towards reduced frequency and increased intensity in most Alpine regions.

1.2 Climate change adaptation in the transport sector

For the transport sector adaptation to projected changes in extreme weather patterns (Koetse and Rietveld, 2009), while keeping in mind the high uncertainty in climate projections (Vajda et al., 2011), costly adjustment of transport infrastructure is not necessarily the most optimal option (Hallegatte, 2009). In turn, this implies that scenario-based long-term climate information is rarely the key driver behind climate change adaptation (CCA) decisions (Love et al., 2010). Instead, the focus should be on finding strategies and adaptation measures which take into account the changing climate, whilst also addressing the inherent uncertainty related to climate change. To address this issue, robust CCA decisions and strategies, which are insensitive to the uncertainty related to the future climate, have been suggested (Dessai and Hulme, 2007; Hallegatte, 2009).

The provision of weather information can be considered a robust CCA strategy for the transport sector, as weather services are beneficial for road transport in the current climate and with current level of services. However, different processes in nature and society co-exist that shape the future of road transport; climate change is altering weather variability, whilst innovations in weather and climate services and technological development in road transport sector are changing the way services are provided and how the services are used by vehicle drivers, thereby affecting the overall safety of the road transport mode.

The use and value of current weather services in the road transport sector have been studied for instance in Frei et al. (2012), Nurmi et al. (2012) and WIST (2002) (see Section 5). Some research on

how innovations, such as intelligent road transport systems (e.g. Innamaa et al., 2012; Ezell, 2010) can be used to increase the function of road transport in the future has been undertaken. Regarding weather services, much of the research has focused on the development of specific technologies to improve these services, such as using vehicles as observation devices (Drobot et al., 2012) or developing new communication channels to reach the drivers (Roine, 2010).

1.3 Aim and objectives

Innovations in weather services and consequent increases in the benefits of weather services have the potential to improve the resilience of the transport sector to the expected adverse impacts of climate change. The aim of this study is to evaluate how potential innovations in weather services can reduce weather sensitivity and, consequentially, decrease the negative effects of climate change in the transport sector, and particularly the road transport sector.

The study focuses on the road transport for two reasons. Firstly, it is the most vulnerable transport mode to extreme weather, at least if assessed in terms of the aggregate costs related to extreme weather events (Nokkala et al., 2012). Approximately 10% of the road accidents can be attributed to extreme weather events (Nurmi et al., 2012) which translates into extreme weather related losses of over 20 billion euros per year in Europe (Nokkala et al., 2012). Secondly, it serves as a good example to illustrate how innovations in the provision and use of weather information can prove to be beneficial for adapting to the changing climate.

The objectives of this paper are to 1) identify and describe the main trends and potential innovations in the provision and use of weather services in the road transport sector (section 4); 2) identify where in the weather service provision value chain these innovations would have an impact on the use of weather information before and during the trip (Section 5); and 3) analyse the expected magnitude of the value of these innovations (Sections 5 and 6).

The overall purpose of this work is to contribute to the understanding of the overall effects of the improved weather service provision on the safety of road transport to improve climate change adaptation in the road transport sector.

2. Weather services to support climate change adaptation in road transport sector

2.1 Climate Change Adaptation

This paper utilises the approach provided in Smit et al. (2000) to systematically specify and characterise CCA. This approach is based upon responding to the following three questions: 1) Adapt to what? 2) Who or what adapts? 3) How does adaptation occur?, which are outlined below.

1. Adapt to what?

The uncertain, and changing, extreme weather patterns are considered to be the most urgent threat to road transport (see Section 1). Direct impacts of climate change will occur due to, for instance:

- changing freeze/thaw cycles, which will affect winter road maintenance costs and accidents rates (Andersson and Chapman, 2011);
- changing precipitation patterns affecting rainfall, flooding, snow and visibility, which may affect the number of road accidents (Jaroszweski and McNamara, 2014; Jaroszweski et al., 2010; Qiu and Nixon, 2008) and congestion (Koetse and Rietveld, 2009);
- increase in the intensity in hot spells which could increase the accident risk due to psychological and physiological effects (Laaidi and Laaidi, 1997); and

- increase in strong winds, which have a potential adverse effect on road safety (Thordarson, 2006).

2. Who or what adapts?

The most suitable adaptation strategies to climate change are defined by the system in question and its characteristics. The system itself and its need to adapt are defined by various determinants, which measure for instance the vulnerability, resilience and adaptive capacity of the system to climate change. In the road transport sector, different responses are required at operational and structural levels. At the operational level, the role of the vehicle driver is prominent, although adaptation at the infrastructure level, for instance relating to traffic flow management, may become necessary as well. Vehicle drivers respond to quickly unfolding extreme weather events with short lead-times by adapting departure time, changing the route, switching travel mode, and by cancelling the trip. To long-term developments, vehicle drivers can respond by adapting their decision on vehicle ownership, by moving residence or changing a default shopping location. (Hensher and Brewer, 2000; Polak and Heertje, 1993)

At the structural level, measures regarding the capacity, location, and technical standards of transport infrastructure are required. The focus of this paper is the use of weather services as a robust adaptation measure; therefore, CCA is not assumed to take place at the system level, but to be implemented at the level of the user, as vehicle drivers are vulnerable to climate change effects due to changes in the extreme weather patterns.

3. How does adaptation occur?

Adaptation can refer to both natural and manmade systems and may entail both autonomous adaptation, in which a system responds to climate change spontaneously, and planned adaptation, in which deliberate adaptation strategies are developed and measures implemented. This is linked to the timing of adaptation, which can happen prior to any impacts (anticipatory), while the impacts are occurring (concurrent) or be reactive and take place only after the impacts have occurred. Furthermore, adaptation to climate change can be either incremental, if the system is changed by merely extending the current practices which are used to adapt to weather events, or transformational, if adaptation entails far reaching changes in the considered system. (Carter et al., 1994; Smit et al., 2000; Kates et al., 2012)

Due to the uncertainty of the extent of climate change in the future climate (Vajda et al., 2011) and the aforementioned impacts, robust (i.e. valid in many scenarios), yet adaptive, adaptation strategies may be a wiser approach as compared to major infrastructure investments (Dessai and Hulme, 2007). This consideration is based on option value theory, for instance “the benefit derived from keeping options open so as to be able to adjust policies in the light of better information” (Ingham et al., 2007) and to avoid sunk costs (Hallegatte, 2009). With regards to robust adaptation strategies, Hallegatte (2009) suggests the following: *No regret* measures which create benefits even in the absence of climate change; *Reversible* measures which are easily retro-fitted if climate change projections turn out to be wrong; *Safety Margin* measures which reduce the vulnerability of the system at a low or no-cost; *Soft* measures which can be institutional or financial; *Reduced time horizon* measures which involve reducing the lifetime of an investment; and strategies which have *Synergies with mitigation*.

A further classification of adaptation measures is proposed in Perrels et al. (2013a). This classification is based on whether the measures are to reduce (1) exposure; (2) vulnerability, or to (3) improve (active) resilience. Improving weather information belongs to the third category. Due to its ‘active nature’, it blurs the distinction between planned and automatic adaptation, and thereby it may also link incremental and transformational adaptation. As Rotmans and Loorbach (2009) indicate, transformations cannot be fully planned, but can be promoted and facilitated inter alia by enhancing automatic adaptation capabilities through innovations.

This study builds on these definitions and observations and aims to identify to what extent innovations in weather services can help to improve anticipatory, planned adaptation to climate change in the road transport sector, whilst at the same time open up options for more fundamental changes (transitions) in the system. A key element in this respect is the provision and use of weather information so as to enhance well informed decision-making.

Weather information is beneficial for the road transport sector only if successfully used. Therefore, innovations in weather services should focus on the entire weather service chain (including forecasting, information tailoring, media choice, access, comprehension, leeway for response, benefit retention) in order to maximize the leverage of the improvement efforts. (Perrels et al., 2013b)

2.2 Weather Service Chain Analysis

Weather services can be considered a robust, no-regret adaptive CCA measure, as they provide active resilience in current and future climates. For instance, Hallegatte (2009) suggests that early warning systems are a 'no regret', reversible, and soft measure to respond to climate change impacts.

Weather information can be understood as a factor in a decision process aimed at maximizing the value or utility of a considered process or activity. A hypothetical maximum benefit potential of meteorological services can be estimated, assuming that perfect initial information (e.g. perfect weather forecast) is combined with 100% use among end users and 100% effectiveness of their responses. However, the actual level of realised benefits depends on the quality of the information, and the timeliness and ability of the involved users to respond to the information. (Perrels et al., 2013; WMO, 2012)

The actual value of the initial meteorological information stems from the use of the information and the extent to which the end users are able to interpret and use the information and transfer the benefits to other agents. An important aspect in the approximation of the actual level of realised benefits is the information decay in the service chain. Weather Service Chain Analysis (WSCA) (Nurmi et al., 2013) aims at accounting for the inadequacies in the dissemination and use of weather information. The approach describes the decay of the benefit potential based on a decomposition of the information flow, ranging from information generation to benefit realization for the end-user and society as a whole.

This approach has been used extensively in section 5, in which each step (apart from 7 which would require macro-economic analysis) is analysed with regards to how vehicle drivers are able to use and benefit current and improved weather information. WSCA can be used in a semi-quantitative way indicating orders of magnitude of improving potentials per step (which can be related to managerial actions aiming at that step). WSCA can also be used in a more formalized fashion, resulting in estimated fractions, e.g. for the purpose of cost-benefit analysis of a weather service. The seven steps of the WSCA assess the extent to which:

1. Hydro-meteorological information is accurate [accuracy];
2. Information contains appropriate data for a potential end user [appropriateness];
3. The end user has (timely) access to the information [access];
4. The end user adequately understands the information [Understanding];
5. The end user responds to the information to effectively adapt behaviour [responsiveness];
6. Responses actually help to avoid damage or improve operations [response effectiveness];
7. Benefits from adapted action or decision are transferred to other economic agents.

The estimate of the overall effective avoidance share Q can be calculated with the following equation; bearing in mind that the linear structure of the model gives only an approximation of the value decay in each step ($S_1...S_6$):

$$Q = \prod_{s=1}^6 \{S_i\} \quad (1)$$

The weather service market is essentially based on observing and predicting weather and effectively communicating the produced information to users. While this structure remains, in the process of innovation the components of the market undergo changes. The technology develops, enabling improved level of both temporal and spatial accuracy, and meanwhile also the communication channels develop and change. As Bayesian decision-theory suggests, improved level of information only brings incremental value if it has an effect on the decision-making (Katz and Murphy, 1997).

Consequently, we use WSCA in conjunction with decision-analysis by analysing the decision-making process of the vehicle drivers. This approach requires mapping of the following information: (1) relevant decisions for a user (or user group) for which weather information has a differential effect; (2) need to identify what are the relevant future possible events that may occur and the economic consequences of those; (3) how well the different stages of the WSCA are realized at the moment, and (4) which parts of the chain will or should develop in the future to create economic benefits.⁷

3. Methods and data

Semi-structured interviews were performed to identify the trends and potential innovations in the provision and use of weather services and analyse the value of these innovations in the weather service provision value chain. Semi-structured interviews have a planned interview guide, but are open to new topics, as it allows exploring of new areas emerging during the interview (Gillham, 2005). The interview guide used was designed based on the WSCA, described in Section 2.2. Altogether 12 semi-structured interviews were undertaken during the spring of 2013 by the two first authors of this paper.

Out of the 12 interviewees, eight represented a national hydro-meteorological service (NHMS) and were experts on weather and transport, or service or business development. Requests for interviews were sent to several European NHMSs, and interviewees were selected in order to obtain a balanced representation of all aspects of meteorological and climatological development. Furthermore, three experts in the areas of weather observations equipment and related technologies were interviewed. In addition, a winter road maintenance company was interviewed to gain an understanding of the link between weather information and road-users. The winter road maintenance company is one of the two big players in Finland that share regional maintenance contracts. It has an almost identical operational structure to that of many countries, for instance, in Sweden, Norway and Canada. Individual driver behaviour was analysed through literature (Sihvola and Rämä, 2008; Cools and Creemers, 2013).

The purpose of the interviews varied according to the stakeholder category:

- NHMS: to identify the services provided for road transport sector and the main trends in new meteorological services;
- weather forecast model developer (European Centre for Medium-range Weather Forecasts): to determine the expected future capabilities of weather models and their dependence on the investments;

⁷ A classical reference for decision analysis approach regarding weather information is Katz and Murphy (1997)

- weather observations equipment supplier: to determine the development of the observation network as an enabler of more spatially accurate weather information;
- expert/professor on information, communication and networking technology: to understand technological development and innovation processes in information and communication technology, particularly related to weather service provision
- Interface between weather service provision and road users: to understand the current use of weather and climate information to ensure safe driving conditions for the vehicle drivers, the need for improved information and how climate change is expected to change the operational environment and data needs.

All interviews were transcribed verbatim and coded and analysed independently by the first two authors of the paper. The interviews were coded with respect to three aspects: 1) who is the target or the user of the innovation in the weather service provision (road maintenance companies, professional drivers and normal vehicle drivers); 2) what type of weather or climate forecasting is the innovation expected to improve (nowcasts⁸, short-range weather forecasts [up to 72 hours], medium-range forecasts [up to 10 days], monthly forecasts and seasonal forecasts); and 3) in which step of the WSCA is the innovation considered to be relevant (introduced in section 2.2).

4. Foreseen innovations in weather services

Based on the results of the semi-structured interviews, the overall trends and innovations in meteorological services up to 2030 can be classified into three categories: observation technology, global weather models and information and communication technology (ICT).

4.1 Observation technologies

Observations (either with radar instruments, meteorological satellites or mobile devices) are the starting point of any meteorological work and an important factor behind improved weather forecasts is a dense and reliable observations network. Therefore, innovations in the coverage and reliability of observational instruments are highly significant in determining the future capabilities of weather forecasts.

The current state-of-the-art radar technology is the *dual-polarization radar*, which observes both the amount and type of precipitation – being water, sleet, snow or hail. All new radars installed in developed countries are dual polarization radars. As of 2013, 40 out of the 200 radars in Europe have already been updated. The remainder are expected to be replaced by 2025.

Adaptive radar networks, which allow multiple radars to flexibly follow the development of a relevant weather phenomenon, reduce prediction uncertainty in nowcasting. More reliable nowcasting enables decision-makers to make better decisions in situations in which the costs of the incident, but also those of false alarms are significant. (McLaughlin and Chandrasekar, 2009)

The *improvements in the satellite observation systems* in the past two decades have been a crucial driver behind the steady extension of the reliable forecast period. Future improvements in satellite systems can be expected to continue this trend. However, growing uncertainty about funding of these future systems seriously challenges the assumed trend.

The further development of retrieving and analyzing mobile observation data was emphasized by the interviewees. *Mobile observations* include observations from vehicles e.g. data from the windscreen wipers or braking systems, and observations made by individuals with mobile devices. These observations can be automatically collected data in a specified format. A novel approach is to compose informal data points such as pictures or status updates posted in social

⁸ Nowcasting concerns very short term weather forecasting 0 – 4 hours ahead at high spatial resolutions (such as road segments) (Browning, 1980)

media (e.g. Hyvärinen and Saltikoff, 2010; Muller et al., 2015). Due to the possible quality problems with this kind of data, it either requires validation or it can be used for validation purposes.

Data fusion means that observational data from different sources, for example measurements from weather stations, road-side rainfall measurements and lightning data is combined and analyzed in conjunction with radar data. Consequently, integrated measurement networks would provide a better picture of the state of the atmosphere. Open data policies, such as the INSPIRE directive by the European Commission (European Parliament and Council of the European Union, 2007) will enable also private weather companies to develop tailored applications based on data fusion.

4.2 Global weather models and forecast skill

The performance indicator representing the capability to predict meteorological conditions is indicated by 'forecast skill'. Nurmi et al. (2013) suggest that atmospheric predictability has improved approximately by 1-day-per-decade during the last 20 years; which was confirmed by ECMWF. Generally, for a given season and area, temperature forecasts tend to perform better than precipitation forecasts. The 1-day-per-decade development is a baseline for the expectation of the development in the future, but it requires some assumptions on technological development and policy measures. The biggest threat to the continuation of this improvement rate stems from research and development budget constraints. The development depends largely on the following three factors:

1. *Computing power*: with faster computers, models can run at higher resolution and phenomena that happen in the atmosphere can be better resolved. The decreasing cost of processing power also enables more sophisticated observation and data transmission instruments and in general lowers the price of all data processing.
2. *Observation infrastructure, especially meteorological satellites*: Running models at a higher resolution requires higher resolution satellite data, which requires maintaining a sufficient satellite fleet and systematic renewal of obsolete satellite instruments. For shorter range forecasts, conventional observations systems are more important, requiring investments in this infrastructure as well.
3. *Computer models, and general meteorological research*: Research is required on the interactions between the atmosphere, land (e.g. vegetation) and ocean and on running the models in an efficient way. Furthermore, the utilisation of the advancements in computing power requires development of more sophisticated models.

In addition to temporal accuracy, also the spatial accuracy of global models has been increasing steadily. ECMWF expects to run their global forecast system in a 10x10 kilometre grid within the next five years and perhaps in a 1x1-kilometre grid in 10-20 years. Current regional very high-resolution models run in a 3x3-kilometre grid. As the spatial accuracy of these models and predictions increases, the role of NHMSs could change, as they are currently the main providers of regional weather forecasts. This could lead to significant rearrangements in the division of responsibilities between different service providers; public and private alike.

4.3 Information and communication technology

As mentioned, ICT has a key role in the development of weather and climate services. Improvements in weather forecast accuracy are partly enabled by advances in computational capabilities. Smoothly working telecommunications are critical for the timely access to weather information; the use of mobile observations increases the reliance on communications even further as the data has to flow in two directions. Combining spatially and temporally accurate weather data with other context-dependent information requires both abundant transmission and processing capacities.

Advances in electronics have enabled the continuing reduction of unit costs in computing and telecommunications. The physical limits of current transistor technologies are acknowledged, but the exponential development is expected to continue in the following decades (Cavin et al., 2012). Thus, the development of computational performance is likely to support improvements in forecast accuracy also in the future. There are, however, other technical challenges that may affect the course of weather service innovation. Firstly, congestion of mobile networks is worsening as both the amount of mobile devices and the popularity of data-intensive services increases. Technological development alleviates the problem to some extent, but the spectrum itself is limited. For example maintaining a reliable road weather service might require specific policy decisions at some point. The second challenge is the growing energy demand of the mobile devices. More advanced network technologies require more advanced signal processing from the device. This, together with the higher capabilities of the devices regarding their computational power, display quality and other features translates into rising power consumption. Although the issue could be addressed with improvements in battery and charging technologies, a more fundamental problem is caused by the waste heat that needs to be dissipated. This problem is however less relevant for road weather systems if the end-user devices are part of the vehicle.

Any advanced road weather system needs to combine and process data of various sensors and sources. Foreseen technological development enables further advancements in such systems, but the aforementioned challenges are likely to guide their design. In light of the challenges, the road weather systems are likely to be centralized (data gathering and processing taking place in a remote service centre) instead of decentralized (data gathering and processing taking place in the vehicle). The configuration of the system will also affect the business models and the diffusion pattern of the services.

5. Innovations in weather services as a means of adaptation in the road transport sector

The use of weather and climate services is closely intertwined with the evolution of a road transport sector's coping range with respect to prevailing weather conditions. Consequently, investment in weather services is beneficial regardless of the realized future state of both climate and society and is, therefore, a robust adaptation measure. The development of weather and climate services can expand the amount of cost avoided, and/or enable improvements in conjunction with product or process development in the road transport sector. This means that adaptation to climate change will be affected by the socio-technical innovations in weather and climate services.

The responses arise either when the weather condition becomes apparent or when the information about the current/future weather conditions reaches the decision-maker. There have already been positive findings suggesting that these measures can decrease the economic sensitivity of the transport sector to weather conditions (Lazo et al., 2011; Nurmi et al., 2013).

This section shows how innovations in weather services can enhance these decisions and increase the benefits of the information for the users. Using the first six filtering steps of the WSCA, we analyse how the investment in weather service capabilities affects the ability to respond to adverse weather conditions. This is done by analysing pre-trip and en-route adjustments. The current level of each step is analysed mainly from the results of the relevant literature, while the innovation prospects and service development were collected from semi-structured interviews (section 3).

Ideally, the (accurate) weather information should be available for the vehicle drivers at the latest on the evening before the trip because they request knowledge about the relevant weather parameters 6-12 hour prior to trip to be able to modify their travel plans (Nurmi et al., 2012; WIST, 2002). On a shorter lead-time, the modifications are more of a reactive nature, such as

selection of a different route (Cools and Creemers, 2013). The relevant weather parameters, which climate change is projected to have an effect include at least snowfall, precipitation, temperature, wind gusts and hail (Vajda et al., 2011; Jylhä et al., 2009).

In addition to pre-trip decisions, vehicle drivers can adapt to current weather information by making en-route decisions. Rather than a static decision, an en-route decision is a recurrent or even continuous series of decisions related to driving speeds, effective route choices, stoppages, safety margins and overtakes. Results from earlier studies suggest that on-road driving behaviour is predominantly affected by the prevailing conditions rather than traffic weather forecasts (Kilpeläinen and Summala, 2007; Nurmi et al., 2012; De Palma and Rochat, 1999). However, it seems that up-to-date information during the trip can have a larger impact on the drivers' response. Consequently, the most important meteorological information are nowcasts and observations from road weather stations. The methods for improvement of the efficiency of on-road decision-making should be spatially very accurate, technical by nature and give clear messages of effective/suggested measures (Kilpeläinen and Summala, 2007). These measures could shift the en-route weather information from static weather maps to dynamic decision-making tools such as adaptive route-choice tools.

5.1 Step 1: Accuracy of relevant weather parameters

Based on indirect verification methods (Sihvola and Rämä, 2008), 92% of the days with very poor weather conditions are at the moment forecast already on the previous evening.

Pre-trip decisions

Often, weather parameters relevant for vehicle drivers are combined in a road weather model, which employs as an input a numerical weather forecast and observations from synoptic weather stations, road weather stations and weather radars. The model produces a forecast of road conditions (e.g. friction and visibility), which can be categorized for instance in three classes; 'normal' which implies normal driving conditions and is disseminated as a regular forecast, 'difficult' and 'very difficult' which are disseminated as warnings to the public. Based on an indirect verification of the quality of the extreme winter weather warning system in Finland, warnings are successfully issued on days with a distinctly high accident rate; 19 out of 21 of the days with highest accident rates had been forecast on the evening before (Sihvola and Rämä, 2008), indicating that existing road weather models are fairly accurate in predicting the worst accident days. Direct verification is difficult since no objective measures for poor or very poor road conditions exist.

However, Juga (2012) suggests that a surprise factor due to a missed adverse weather event by a forecast is an important determinant in accident rates, implying that no warning can result in very high accident rates on a given day. Furthermore, Sihvola and Rämä (2008) found that poor or hazardous road weather conditions had been forecast on days when the realised accident rate remained low.

Due to the non-linearity suggested in Juga (2012) and false alarms detected in Sihvola and Rämä (2008), the improvement in the temporal accuracy of road weather models can result in large economic savings, as the forecast at the time point of the requested lead-time (6h-12h) is becoming increasingly accurate as discussed in section 4. As an interviewee pointed out, this increases in importance due to the projected climate change-induced increase in weather variability and potential increase in the surprise effect.

En-route adjustment

The most important feature of meteorological information for en-route decisions is spatial accuracy of road condition nowcasts. Of the NHMSs interviewed, two considered the quality of the observations from road weather stations as 'good'. However, the weather station network often is not of the required density, is only concentrated in densely populated areas or is along

the main road network. As mentioned by two NHMS interviewees, this greatly challenged the feasibility to produce spatially accurate forecasts and nowcasts.

To tackle this issue, the technology supplier and the NHMSs suggested two main improvements in observation technology. Firstly, the technology supplier noted that less expensive technology, in the form of *remote road surface state sensors* which enables a denser observation network, has been developed. The installation of these devices is expected to start well before 2020. Secondly, mobile observations have the possibility to create a denser observation network, as for instance vehicles can provide information on road slipperiness from the tires and precipitation volume from the windscreen wipers. NHMSs suggested that this process is likely to happen in the next ten years. However, to maintain quality standards of the localized forecasts, verification of the mobile observations with the nearby (road) weather stations is required. Further development, where cars could communicate weather information to each other without a meteorological service as an intermediate, is in progress. Without verification and quality check by a meteorological service, these services can turn out to be problematic. Furthermore, adaptive radar technology and data fusion introduced in section 4 will enable spatially more accurate nowcasts. The new applications will be available in the next 5-10 years (2020-2025).

5.2 Step 2: Appropriate data

Based on the literature review and NHMS interviews, the three-level-index about the road conditions is considered sufficient but not exhaustive information by the vehicle drivers. There is demand for route specific information and combination of road condition data with other relevant data (e.g. road blockages). Current skill rating is still around 90%, since based on interviews and literature (Sihvola and Rämä, 2008) the road weather warnings would already enable informed decisions, if utilised accordingly (see steps 4-5).

Pre-trip decisions

The three-level road weather forecast and warning system is well understood and intuitive to vehicle drivers, according to a user survey conducted by one of the NHMSs. However, according to the survey, vehicle drivers would like to obtain more specific information on the actual timing of the adverse weather, as current road weather warnings usually show similar adverse conditions for the next 24 hours, and more specific information on the actual location of the weather event. This demand was specifically mentioned by two other NHMSs interviewed. However, this demand creates a challenge for the communication as giving detailed temporal information via the traditional dissemination channels (e.g. TV, radio) would require showing multiple weather maps, longer air-time for weather forecasts and harder interpretation of the information. New communication channels, mainly internet and mobile applications are being studied, and new services are expected to emerge in the following years in many countries. This, combined with the improvements in forecast accuracy, enable more time and location specific information.

Route-specific forecasts are already available for road maintenance purposes. These will reach the public in the upcoming years as they are being developed in three of the interviewed NHMSs. In Spain, a pilot project on route-based forecasts for three test-case highways has been implemented through an EU FP7 funded project called FOTsis (www.fotsis.com/).

In addition to weather conditions, more informed pre-trip travel decisions should take into account other relevant information, such as road blockages (e.g. construction work, summer festivals etc.) or expected amount of traffic, pointed one of the NHMSs. An example of such data combination is offered by the Bavarian traffic information agency (Bayerninfo-see <http://www.bayerninfo.de/planner>) which, next to weather information, offers information on real-time events, traffic conditions, travel times and multi-modal services (Scheider et al., 2010).

In Finland, new services that combine data from different sources, and new online and mobile applications that would enable the technical execution, have been planned. In the UK, Met Office

has a system which is designed to forecast weather for different routes for road maintenance purposes. It is based on the road weather model of the UKMET, but has a much higher spatial resolution and accounts also for non-weather factors. These services are not available to the public yet, but are expected to be opened for wider use before 2020 and will likely to be integrated to other route-planning tools in the future (2020-2030).

En-route adjustment

Since drivers tend to underestimate the severity of driving conditions compared to what expert reviews or road weather station information would suggest, bringing up-to-date information of the current road conditions to the vehicle drivers is important. Especially the slipperiness of the road surface is a challenging parameter for the vehicle drivers to estimate through their own perception. (Kilpeläinen and Summala, 2007).

A combination of appropriate road condition, weather data and relevant data from other sources, and effective real-time communication to the vehicle drivers is at the heart of Intelligent Transport Systems (ITS). For instance, one of the interviewed NHMS mentioned that layer-based technology will allow users to select the relevant weather and other parameters to be shown on the screen of a navigation system. An EU FP7 funded project ROADIDEA which studied innovations in transportation, listed this as the main development target in the near future. Furthermore, inaccessibility of data and the location of data collection and calculation were listed as the main barriers for development. (Roine, 2010) ITS was mentioned as an important field of research in the interviews. The development is a high priority for NHMSs (2015-2020), but also for many private weather companies.

The driving and management control in road transport is increasingly integrated into technical systems which adjust to different driver needs. The vehicle infrastructure integration enables either vehicle-to-vehicle or vehicle-to-infrastructure communications and has the potential to improve the information provided to drivers (Petty and Mahoney, 2007). A leading global example is a real-time in-vehicle traffic information system called *Smartway* in Japan which reaches over 34 million drivers. Japan invests over 500 million euro annually into ITS (Ezell, 2010). In the European Union, smart transport solutions are applied; however, in a fragmented manner, in mono-modal instances, in geographically isolated domains, and incompletely (European Union, 2011).

Implementation of ITS requires intensive cooperation between public authorities, regulators, the automotive industry, road infrastructure management, NHMSs and/or private weather information companies, cloud service providers and other agents in the evolving field. This change does not take place instantly and without significant investments in Europe (2020-2040). Meanwhile, the development of "traditional" sources of information such as radio, satellite navigation devices (-2020) and mobile applications (-2020) will be important.

5.3 Step 3: Access to weather information

Currently, approximately 60% of the drivers have actively or passively received weather information prior to their trip (Cools and Creemers, 2013; Sihvola and Rämä, 2008).

Pre-trip decisions

Traffic weather information systems should be easily accessible to drivers and used by a considerable proportion of them to have an effect on traffic safety and pre-trip decisions. In principle, information is accessible to everyone constantly through various channels: radio, television, internet and mobile applications for different platforms. However, according to road side surveys, user rates for road weather information remain somewhat low (Kilpeläinen and Summala, 2007; Sihvola and Rämä, 2008). In a road side interview by Sihvola and Rämä (2008), 62% of the drivers had actively looked or passively received weather information prior to the trip. In Belgium, a study found that 60% of the respondents acquired weather information on a

daily basis; television being the most important medium. However, the choice of media did not play a significant role in the travel behaviour. (Cools and Creemers, 2013). Furthermore, Kilpeläinen and Summala (2007) find that especially young adults are hard to reach via traditional channels. Therefore, we conclude that currently at least 40 % of the vehicle drivers are not familiar with the road conditions prior to a trip.

Push-based mobile applications were identified by interviewees as one innovation to better reach the public. The applications would use the location of the mobile device and send messages to mobile phones either via pre-installed, which would require cooperation with telecom operators, or downloaded "apps", which would require an active decision from the user to install the app and allow it to send push-messages. However, a steady increase in the use of mobile weather applications has been witnessed in Finland (Harjanne and Ervasti, 2014), and based on a survey undertaken in Canada (Silver, 2014), along with telephone calls, text messages and "Cell-phone pop-ups" were seen as the most preferred media to disseminate weather warnings. Therefore, the potential of the push-based messages can be regarded as substantial. Indeed, several new applications are being developed particularly bearing the hard-to-reach young adults in mind. These services will most likely be available in the near future (2015-2020).

En-route adjustments

En-route weather information is still usually based on traditional car radio system. However, two of the NHMSs interviewed are developing nowcast-based weather warnings that will be communicated to satellite navigation devices. This service is already available in one of the interviewed countries, but only for specific navigation devices. In the other two NHMSs these services were considered to be something that commercial companies should provide.

Services for mobile devices are also being developed. However, the safety aspects of using mobile devices need to be considered; for instance Drews et al. (2009) found that dialling or reading text messages from mobile devices is riskier than speaking on the phone or even driving intoxicated. Thus, mobile services should be developed so that the driver does not need to actively search or even read information. Push-based applications with voice alarms, which would warn automatically if the driver is approaching adverse weather conditions or other disturbances in traffic, are being developed. (2015-2025).

5.4 Step 4: Comprehension of the information

Approximately 85% of the drivers that had acquired road weather information considered it easy to use and interpret. Studies also show that road weather information has the ability to improve drivers' perception of the actual road conditions. (Sihvola & Rämä 2008; Kilpeläinen & Summala, 2007).

Pre-trip decisions

Sihvola and Rämä (2008) suggest that those who had acquired weather information considered it easy to interpret and use. The stakeholder interviews confirmed this fact, revealing that comprehension of the three-level forecast and warning system is not a problem for users.

En-route adjustments

Studies show that the drivers who receive weather information before the trip have a more realistic perception of the road conditions than other drivers. (Kilpeläinen and Summala, 2007; Sihvola and Rämä 2008).

In general, drivers tend to rate the driving conditions to be better than the forecasts or actual observations indicate. Therefore, en-route information can improve drivers' judgement about the current conditions, especially if it is considered more reliable than driver's own perception of the weather (Kilpeläinen and Summala, 2007).

5.5 Step 5: Ability to respond timely and effectively

Sihvola and Rämä (2008) and Kilpeläinen and Summala (2007) show that about one third of those who had acquired weather information prior the trip, had actually changed their travel plans. These studies did not reach those drivers that had already cancelled their trips. Cools et al (2013) finds that 45-60% of vehicle drivers did not respond to weather information; the precise percentage depending on the purpose of the trip. Therefore, a conservative approximation of this step falling between 33% and the average of 45-60% is 40%.

Pre-trip adjustments

In Sihvola and Rämä (2008), one fifth of the drivers had made or had considered making changes to their travel plans based on weather forecasts. In Kilpeläinen and Summala (2007), only 6 % (or one third of those who had acquired weather information) of the drivers reported any changes in travel plans before or during the trip. This study, however, did not reach those who had already cancelled or postponed their trips. Both studies found that approximately one third of those who had acquired weather information prior to the trip had changed their travel plans, and neither of them included those who had cancelled. The most common change was reserving more time for the trip. (Sihvola and Rämä, 2008; Kilpeläinen and Summala, 2007)

Cools et al. (2013) studied the response of vehicle drivers to weather information via questionnaires in Belgium. They found that the response is heavily dependent on the purpose of the trip and the forecasted weather phenomenon. Of the shopping and leisure related trips, a far greater share of the respondents were ready to cancel the trip in case of forecast of bad weather (over 30%) than of the work or school related trips (under 10%). The study showed that people react with high variation to different forecast weather phenomena, in particular more strongly to those weather phenomena that they are not used to.

Based on the interviews, NHMSs acknowledge the problem of low response rates. Response rates can be improved with clearer messages and cooperation with other institutions, such as the police. For example, if extremely poor weather conditions are forecast several days ahead, the warnings can be issued on television channels (although in some countries this is not possible) and other media partners can be informed. The police can advise people to leave their own cars home or work from home, if possible. One of the interviewed NHMSs stated that they have already seen success in the cooperation with the authorities, as the amount of traffic has been significantly reduced during those days that warnings have been distributed actively with authorities mainly in national news. An example of a social innovation is the possibility of replacing work trips by collaborative technologies and working from home when needed. According to a study about New York in 2030, 30% of the commuters would have the possibility to stay home in the case of poor weather. The possibility for telecommuting is likely to improve the ability to respond with trip cancellations (Ukkusuri and Ramadurai, 2009).

En-route adjustments

Driver responses to weather information acquired before the trip are non-existent based on Kilpeläinen and Summala (2007) or of too low magnitude based upon De Palma and Rochat (1999), Sihvola and Rämä (2008) and Rämä and Kulmala (2000). However, up-to-date information on the road can have a larger impact on the driving behaviour (Kilpeläinen & Summala, 2007).

Consequently, examples of measures to improve the response of drivers include standardized variable message systems that display concrete driving behaviour instructions (Kilpeläinen and Summala, 2007), such as maximum allowable speed or painted signs on the road surface that are only visible in specific conditions (implemented in the Netherlands, (Clark, 2012)). Other measures could include push-based instruction from mobile or satellite navigation devices or integrated decision-making systems on vehicles. The latter type of options are expected to be implemented in a somewhat more distant in the future (2020-2040). Based on the interviews and Kilpeläinen and Summala (2007), spatially and temporally accurate warnings could improve the

response of vehicle drivers as they would find the information more reliable than the earlier forecasts.

5.6 Step 6: Actual effectiveness of the responses

Responses, such as cancellations (Maze et al., 2006) or even small speed reductions (Nilsson, 1982), are efficient ways to reduce accidents. Nurmi et al. (2012) estimate this step to be 80%, as responses, should they happen, are effective.

Pre-trip decisions

The effectiveness of responses is mixed (Stahel et al., 2014). Cancellation and postponing of trips are obviously effective ways to mitigate the effects of poor road conditions (Maze et al., 2006). Cancellations of trips are more common for leisure-related trips than work-related trips (Cools and Creemers, 2013; Chung et al., 2005). This suggests that leisure trips are much more sensitive to weather information and weather conditions than work trips. For example, in Kilpeläinen and Summala (2007), leisure trips were clearly underrepresented in the road side interviews during very poor driving conditions, suggesting that most of the trips had been cancelled or postponed. Other possible responses are mode changes and route changes. However, these are less frequently used than postponing (Khattak and De Palma, 1997; De Palma and Rochat, 1999). Admittedly, cancellation and significant postponement of a trip will entail disutility for drivers. Supposedly, a significant part of these costs are not monetized. Conversely, there may be also savings such as unconsumed fuel. These costs and benefits of rescheduling are not taken into account in section 5. The same applies for the secondary cost effects of responses discussed below.

However, other responses next to cancellations are not as successful: even though respondents stated that they had acquired information and sometimes even reserved more time for the trip, the prior acquisition of weather forecast information had no effect on on-road-behaviour, which can be better influenced by real time information (Kilpeläinen & Summala, 2007). In other studies the prior acquisition of weather information has influenced the driving behaviour during the trip by small speed reductions (Khattak and De Palma, 1997; Sihvola & Rämä 2008).

En-route adjustments

Even small changes in average speeds have a significant, non-linear reduction in the accident rates. Variable message signs controlled on the basis of automatic classification of road condition situation were found to reduce the winter-time accident risk by 13% and summer-time by 2% (Rämä and Kulmala, 2000). Nilsson (1982) found that a 1 km/hour reduction in average speed reduced the amount of accidents in motorways by approximately 3-4% and on roads with 50 km/hour speed limits the reduction was 4-6%. Drivers are also found to comply with variable speed limits better than to conventional ones (Scheider et al., 2010). The integration of road weather information, mobile devices, cars and road infrastructure will enable coordinated responses in the future, some decades forward (2020-2040).

5.7 Summary of the innovation prospects

Table 1 summarizes the innovation prospects and combines the relevant expected improvements with the estimate of the uptake schedule. The estimates of the timing of the uptake and the current level of each step are based on the preceding analysis. The improvements are again categorized based on which step of the WSCA they are expected to bring improvements.

Table 1. Summary of the innovation prospects between 2015-2020 and 2020-2030

WSCA steps 1-6	-2020	2020-2030
1. Accuracy	Development of road weather models; denser road weather station network; data fusion and more accurate knowledge of relevant parameters for now casting purposes. Current: 92%	Adverse weather can be forecast 1 day earlier with the current accuracy; surprise events very rare; observations from cars to weather forecasts system, data fusion and adaptive radar networks will improve. Spatial accuracy of current observations and now casts
2. Appropriate data	Development of route-based forecasting; Weather information combined with other relevant information; development of layer-based technology (user selection of relevant weather parameters on one map) Current: 90%	Route-based forecasting available; Relevant information processed and selected automatically for the vehicle drivers
3. Access	Improved internet platforms; mobile applications; push-based applications; satellite navigation systems; Current: 0.62	Infrastructure, including weather services, communicates directly with the information system of the vehicle, ITS;
4. Comprehension	Improved en-route information will enable better judgement on the current conditions; Current: 0.85	Changes in weather parameters automatically analysed by the information systems of the vehicles.
5. Ability to respond	Variable message systems and road signs, concrete and spatially accurate advice from mobile devices and satellite navigation systems. Current: 0.4.	Telecommuting possible for a larger share of commuters.
6. Effectiveness of response	Current: 0.8	Coordinated responses

Figure 1 shows the current level of each step, also given in Table 1. It also shows the estimated increases in the current levels for each step (baseline in Table 2). A tentative system response analysis for the future values is performed in Section 6.

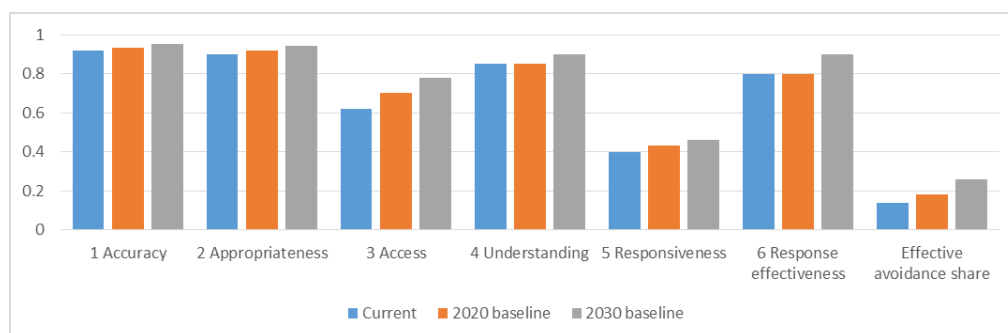


Figure 1. The current level of each WSCA step and the estimated increase in each step

6. Discussion

Road transport is facing two types of trends that are affecting the level of accidents in the opposite directions. The expected increase in the extreme weather related costs is interlinked with

expected decrease of accidents costs due to technological and societal development (Nokkala et al. 2012). There are some estimates of the expected accidents costs taking both of these trends into account (Andersson, 2010; Nokkala et al., 2012) but due to high level of uncertainty of the future state of the sector, it is questionable to use these estimates for economic analysis. Nurmi et al. (2012) estimate that the annual accidents costs due to extreme weather in Europe are currently close to 24.4 billion euros. Consequently, this estimate of current accident costs is used in the sensitivity analysis for the magnitude of the annual savings of the weather service improvements. Nurmi (2012) estimate that only approximately 14% of the hypothetical maximum benefits of weather services (in terms of accident prevention) are currently realized at the end of the weather service chain in road transport. The estimate is based on the decay of value through the entire chain, expressed as product sum as explained in section 2.2. The constituting elements of the product sum, and the eventually resulting fraction realized are shown in Table 2 in the "Current" column. The exact formula of the effective avoidance share was introduced in section 2.

Table 2 presents a tentative system response analysis of how the improvements in the weather service chain would result into economic benefits. This can be viewed as the authors' best guess based on the innovation prospects and earlier experiences summarized in Table 1. The improvements in steps 2-6 in Table 2 are potential development pathways for weather services for road transport. We have developed two futures scenarios - baseline and high investment. The scenarios are developed based on the analysis presented in section 5. In the high investment scenario, progress in each step is defined to be twice as fast as in the baseline scenario. The improvement in step 2 is assumed to be modest due to the high initial value; however, based on the interviews, NSHMSs are putting effort on further improving this step. A larger improvement is assumed in Step 3 where innovations play a crucial role and several new ways to deliver information are being developed. In steps 4 and 6, no improvement is assumed in the baseline scenario until 2020, as this is heavily dependent on the end users and their behaviour. However, with further improvement in technologies, understanding and the effectiveness of the response will improve as more control is given to vehicles. The baseline of Step 5 is expected to improve earlier when more information is provided to the navigation systems.

In the base case, until 2020, 18% of the hypothetical maximum benefits are reached, and until 2030, 26% of the hypothetical maximum benefits are reached. In the high case, until 2020 26% of the hypothetical maximum benefits are reached and until 2030 40%. It is worth noting that this analysis is only done to illustrate how investments in weather services and respective innovations would translate into economic benefits as reduced accident costs. Other savings, such as time savings, should be added to the calculations; however based on earlier studies (Nokkala et al., 2012; Leviäkangas et al., 2007) those are likely to be small in value related to the accident costs. The system response analysis allows decision-makers to compare alternative investment strategies and/or conduct cost-benefit analysis of investment in projects altering the weather service chain. Consequently, the analysis is not meant to give accurate predictions of the future benefits, and the economic benefits should be interpreted as giving the expected magnitude of the future benefits given the chosen investment strategy. Also by manipulating different steps, benefits of investment in particular area of the weather service chain can be approximated.

The annual monetary benefits in the form of reduced accident costs are depicted in the last row. The disparity between base and high scenarios is around 2 billion euros annually by 2020 and already over 3 billion euros annually in 2030.

Table 2. Tentative system response analysis and resulting economic benefits

WSCA steps	Current	2020 baseline	2020 high investment	2030 baseline	2030 High investment
1 Accuracy	0.920	0.935	0.95	0.95	0.98
2 Appropriateness	0.900	0.920	0.94	0.94	0.98
3 Access	0.620	0.700	0.78	0.78	0.94
4 Understanding	0.850	0.850	0.9	0.9	0.95
5 Responsiveness	0.400	0.430	0.46	0.46	0.5
6 Response effectiveness	0.800	0.800	0.900	0.9	0.95
Effective avoidance share	0.140	0.18	0.26	0.26	0.40
Road accident max. damage potential (10 ⁹ €)*	24.4	24.4	24.4	24.4	24.4
Prevented damage costs/year (10 ⁹ €)	3.4	4.4	6.3	6.3	9.8

*current accident costs + estimate of the avoided costs

Table 2 shows that currently the largest gaps in the benefit realisation are related to WSCA steps 3 (access to up-to-date information) and 5 (ability to respond). A large share of the drivers does not acquire weather information prior to their trips and during the trip base their opinions about the weather conditions mainly to their own observations. Therefore, the development in the communication technology is a key driver in this step. New ways to reach the vehicle drivers, such as new applications on mobile devices, services for satellite navigation devices and variable message systems are being developed. On the other hand, based on past studies, it seems that the responses to weather warnings are of too low magnitude both prior and during the trip.

So what are the key investment decisions that affect the realized future scenario and the economic benefits? Policy instruments and economic constraints affect the speed, magnitude and the direction of the innovation. This impact of economic activity and policy on development and diffusion of new technologies can be labelled as *induced innovation* (Nordhaus, 2002). The innovations in road weather services are likely to rely on policy decision in two key ways. First, the development in weather services is highly dependent on enabling core technologies, especially ICT and space technology. The advancements in these technologies are often results of publicly funded basic or applied research or research infrastructure. Thus, public investments are necessary to support the research and development work on which the future road weather services is built on. Second, many of the components in the current and envisioned road weather services are directly reliant on public funding or regulation. The weather observation infrastructure as well as the road infrastructure in general is likely to remain publicly funded. Advanced systems require working high-bandwidth communications across large areas that contain both densely populated urban areas and scarcely populated rural locations. Ensuring reliable communication in these conditions likely requires prioritization on policy level in situations in which the data traffic is congested and subvention in areas where the market is small or undeveloped. Yet, although the development is highly policy dependent, the private sector has a major role in producing and diffusing technical and practical innovations. Preferred policy is then such that it involves industry in developing new services and aims to create incentives for companies to create novel solutions for road weather services.

7. Conclusions

Based on both literature review and the user survey, the expected changes in weather variation and in the extreme weather patterns seem the main threats that climate change poses to transport sector in Europe. However, keeping in mind both the high level of uncertainty in climate predictions and the fact that users of transport modes mainly react to adverse weather at the operational level or at the tactical level, costly alterations in transport infrastructure is not likely to be the most efficient adaptation strategy. Consequently, an important part of CCA in transport sector goes through processes that enable better operational and tactical level decision-making in adverse weather situations. Innovation in weather services is a crucial building block in this process.

The aim of this paper was to assess the role of innovations in weather service provision to reduce the negative impacts of climate change-induced increase in the frequency and severity of extreme weather events in the road transport sector from the perspective of the vehicle driver.

It is clear that the potential value of weather service provision has not been fully realised. Investments in research and development, leading to innovations, were shown to be beneficial in terms of increase in the avoided accident cost. These innovations are examples of the improvements in the weather service chain which will significantly decrease the vulnerability of road transport to extreme weather event and the weather related costs, thus being an important part of the sector's climate change adaptation process. Innovations enhance automatic adaptation capabilities which thereby extend the coping range of the road transport system. In turn this allows us to better exploit learning options and thereby invest later on more effectively in adaptation measures. The benefits of the innovations are naturally dependent on the overall development of society and the climate.

The first limitation of the analysis presented in this paper is the knowledge gap of the impacts of climate change on the transport sector, and consequently the lack of estimates related to the accident rates and costs in future climate and society. Paradoxically, it stems from the same reasons as the suggested need for the robust, no-regret adaptation options.

Another limitation of the analysis is related to the qualitative nature of the WSCA and resulting need to estimate the quantitative level of each step based occasionally only on qualitative data. However, WSCA is a comprehensive tool as it enables to assess the full weather service provision chain from the generation of the information all the way to the end used response and resulting benefits. The development of the WSCA is leading toward quantitative indicators with objective criteria to assess the current status and the development need of each step. This would enable the use of the approach in multiple contexts and more objective estimates of the benefits and development needs. The benefit estimates could be used in cost benefit assessments of selected investments.

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