Weather service chain analysis (WSCA) -
An approach for appraisal of the social-economic benefits of improvements in weather services

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ABSTRACT

The so-called Cost-Loss approach for the assessment of the economic benefits of weather forecasts is less suitable for assessing the benefits for user groups among which uncertainty about the uptake and utilization of the information is significant. Most road users can be counted to these groups.

Assessment of the benefits of (improvements in) weather services for road users faces several attribution problems which may entail both over- and underestimation of these benefits.

In FMI an approach has been developed which aims to account for these uncertainties by means of decomposition of the information flow ranging from forecast generation to benefit realization, i.e. so-called weather service chain analysis (WCSA). This approach can be used both in a quantitative and in a qualitative fashion. The qualitative version is meant to support information management and to identify improvement options in each section of the weather service chain. In the quantitative version the product sum of ratings per step (compared to the maximum score) is established. The quantitative version helps to identify those segments of the chain for which improvements will have the highest social-economic pay-off. It also helps to identify actions that raise the leverage of investments in weather forecast improvement.

The WSCA method can be embedded in the economic modelling of particular sectors, such as (road) transport. WSCA also incites to develop regular surveying of user groups and weather service use. The paper will discuss the principles of the method and its links to economic models, as well as show a few applications for road transport.

Keywords: extreme weather, transport system, weather forecast verification, valuation methods, weather service value chain

1   INTRODUCTION

The traditional approach for the assessment of the economic value of weather information is the so-called Cost-Loss model [1], which is in fact a specific form of a pay-off matrix rooted in game theory. In the Cost-Loss model, taking protecting action involves a certain cost while no protection at all is expected to result in a larger loss if adverse weather conditions occur. The optimal decision whether to protect or not is influenced by prior knowledge of the relevant weather conditions. The weather information provider delivers this information and it can be shown that the better the quality of the forecast the larger the expected value of the decision. This model can be further developed to include the attitude towards risk of the decision maker.

If the uncertainty range around the forecast probability is significant and/or the prevention costs are not the same in alternative weather conditions, the same approach could still be used, but its application gets more complicated. In both the simple and complicated version the effect of the improved average forecast certainty (i.e. higher probability) as well as the reduction of the variability in forecast accuracy can be assessed, provided all other information is available. Furthermore, the method implicitly assumes that all involved actors are

perfectly informed, perfectly knowledgeable about options and perfectly rational. In practice these conditions are to a large degree fulfilled in aviation and to a fair degree in sea transport and electricity generation. For most other user groups this is usually not the case, and therefore additional analysis is necessary in particular about the extent to which imperfections in information use lead to inaction (assuming that the opposite – unnecessary action – occurs much less). To this end weather service chain analysis is introduced.

2 THE CONCEPT OF WEATHER SERVICE CHAIN ANALYSIS

2.1 Introducing the stages in the weather service chain

Various authors have been discussing the limitations of the Cost-Loss approach. Obvious extensions are for example explicit inclusion of uncertainties about the forecasts and about the effectiveness of counter measures [2]. Yet, even though these are useful extensions of the basic Cost-Loss model, various problems are still not addressed, as the approach remains essentially too mechanical for application to non-perfectly informed users. In reality often only a part of the loss can be avoided. Reasons for these limitations are rooted in incomplete information, limited capabilities of decision-makers to interpret information, transaction cost of information acquisition and processing and principal-agent (split incentives) structures. Thereby the value added derivable from the weather forecast is in fact dependent on the entire weather service chain from the weather information generation to the actual response.

In relation to forecast skill indicator development several authors have already hinted at the need for elaborating the evaluation of the forecast quality beyond the basic cost-loss model and its variations. On the one hand some strains of development try to account the effects of uncertainty and confidence on the use of weather information with more sophisticated ways [3]. A second line deals with variations in the appreciation and uptake capability of the weather information by the user [4; 5]. Combinations of the two approaches are truly scarce (an example is [6], e.g. because management of the complexity of the different components. Below we will show that the inclusion of the user side or rather the entire pathway from forecast to the realized benefit needs to be accounted for in order to get a better appreciation of the socioeconomic value of the weather services. The addition of uncertainty is basically a more technical feature, which is relevant, but gets only a practical meaning in the valuation if the uncertainty can be sufficiently specified (and preferably empirically tested to get a hunch of the distribution characteristics). Furthermore one should realize that uncertainty in many forms is an issue throughout the entire pathway from the forecast to the realized benefit and not just for weather forecasts as such.

It is necessary to understand the complete process of translating changes in the forecast accuracy into values for the end-users. Perrels [7] decomposes the stages during which the value is created. He presents seven filters which forecast services are passing through when considering the entire chain from the forecast generation to the realized benefit for the end-user. These filters or stages reduce the potential benefits that a perfect weather information system could realise. The stages are:

1) the extent to which weather forecast information is accurate
2) the extent to which weather forecast information contains appropriate data for a potential user
3) the extent to which a decision maker has (timely) access to weather forecast information
4) the extent to which a decision maker adequately understands weather forecast information
5) the extent to which a decision maker can use weather forecast information to effectively adapt behaviour
6) the extent to which recommended responses actually help to avoid damage due to unfavourable weather information
7) the extent to which benefits from adapted action or decision are transferred to other economic agents

The more professional and meteorologically skilled the end-user is, the less the stages beyond forecast accuracy (steps 2-7) affect the attainable value added generated by the use of weather services. Thus, better accuracy and lead-time of weather forecasts (step 1) might create a significant increase in the value just from these improvements for the most professional users. As regards to transportation these users might include decision-makers in aviation and marine navigation industries. On the other hand for road users (in particular non-professional traffic modes) the significance and improvement potential of the steps 2-7 will weigh more. Therefore, these filters need to be studied in a greater detail depending on the traffic mode.

The above 7 stage list can be used both in a managerial indicative fashion (e.g. by adding options for improvement) as well as in a quantitative analytical framework. Table 1 provides an example for a mainly qualitative review. A formalised summary of the WCSA approach is presented section 2.2.

Table 1 Qualitative assessment and recommendations per step with some backing by observations

	Filtering steps	*Present qualities and room for improvement*
1	*weather forecast accuracy*	**generic**: up-to-date and well maintained weather observation and forecasting system; adequate and 24x7 staffing; monitoring and evaluation of forecast accuracy. **observations**: accuracy levels good, 92% or 19 out of 21 adverse weather days were predicted [8]
2	*information/message customer orientation*	**generic:** skilled editing of technical forecast information into textual and pictorial information which exactly appeals to the information needs of the targeted user group; well-tended and lasting customer relation for guidance on what's needed (both end-users and media channel managers are customers, see also no.3). **observations**: road weather warnings are well understood by drivers – about 90% of people understand what is meant by "normal" "poor" or "very poor weather" [9;8]
3	*access to weather information*	**generic:** ensure distribution of weather information through a diversity of media channels in order to reach as many as possible different user types as well as to ensure back-up in case of emergencies; tune information to the typical user-interfaces of each media channel; agree with media channel managers on technical and economic access features **observations:** high availability, user rates however only about 62 % [8] messages needed about current road weather conditions including in-car systems and road sings [10]
4	*comprehension of the information*	**generic:** easy to grasp representation of information; communicate and educate standard terms; build trust (incl. possibilities and limits of forecasts) – this links back to accuracy quality and its evaluation as well as customer relations elicit interest for further education, e.g. via schools, radio and via customer relations **observations**: People mostly use personal observations over real weather information [11] bad judgements about current conditions, weather information makes the judgement about current conditions more accurate [12] – 85%
5	*ability to respond timely and effectively*	**generic:** ensure timely availability of weather information (hence the 24 x 7 staffing need and the agreement with media channels on access **observations:** the frequency of bad weather warnings sufficient for timely responds [13], but too high threshold for adjustments [11], education needs about driving in bad weather conditions and the use of weather information – only 20% of all drivers change their decisions, however people with weather information make changes more often than other drivers, circa 40%. More study needed on this area.
6	*actual effectiveness of responses*	**generic:** this step is to a significant extent outside the realm of influence of the weather service provider, but promotion of education on (use of) weather information will help (step no. 4) **observations**: mostly right responses: (earlier departure from home, lower driving speeds, cancellations of trips and different routes used), however changes happen with too low magnitude: speed reductions too low, only 2% lower volume on road traffic when poor weather warning issued [11] – we give numerical value of 80%
7	*incidence of the costs and benefits of the response*	**generic:** awareness on who is eventually benefitting is important to understand; part of the benefits to vehicle drivers due to lower costs of driving, network analysis needed to estimate mode substitution

2.2 Formal representation of WCSA

Assume that a value chain consists of s consecutive stages (where s = 7 in this case). For each stage a share or propensity P_s can be established, which denotes the extent to which the performance in that stage deviates from the maximum attainable performance of that stage. Apart from the first stage, in which performance denotes forecast accuracy, in all other stages performance includes the notion of maximum number of users (which is able to receive, understand, use, etc. the information). For a particular type of transport mode in a particular period (year) the realized fraction Q_{mt} of a hypothetical maximum benefit potential score is:

$$Q_{mt} = \prod_{s=1}^{7} \{P_{ms_t}\} \tag{1}$$

where $0 \leq P_{ms} = f_{ms}(x_{s_i}; \ldots; x_{s_{i+n}}) \leq 1$, and therefore also $0 \leq Q_{mt} \leq 1$

The realized benefit for mode m in year t (B_{mt}) is the product of Q and the hypothetical maximum benefit score, corrected for possible non-linearity effects between the achieved fraction Q and realized benefit B_{mt}:

$$B_{mt} = Q_{mt} \cdot \gamma^{\alpha(1-Q_{mt})} \cdot B_{m,t}^{max} \tag{2}$$

The establishment of the hypothetical maximum score $B_{m,t}^{max}$ can be realized in several ways. One option is to elicit expert opinions in a structured deliberation process, such as Delphi and group decision analysis, and eventually apply – possibly weighted – averages. Another option is to start from some gross estimate of weather related cost effects for the considered mode. This would indeed represent a hypothetical upper bound, since a part of those effects cannot be mitigated at all or at least not by weather service improvements alone. The latter option ties in with the production function approach in chapter 2, i.e. ΔQ as first approximation and offers possibilities to link this approach to macro (sector) scale assessments of the induced benefits of weather service induced reduced vulnerability.

The scores of P_{ms} in the stages 2 to 7 are (target) population averages. So if there are N actors in M relevant target groups, P_{ms} is defined as:

$$P_{ms} = \frac{\left[\sum_{j=1}^{M} \sum_{i=1}^{N} p_{j,i} \right]}{M.N} \tag{3}$$

for $s = 2 \ldots k$ (with $k = 7$ in this case)

These scores per stages are assumed to follow typical saturation patterns, which can be adequately represented by logistic models. So, for each actor I, from target group j, a binary logit function can be estimated:

$$p_{j,i} = \frac{e^z}{1+e^z} \tag{4}$$

where z is explained by one or several background variables

$$z = \beta_0 + \sum_{i=1}^{n} \beta_i x_i \tag{5}$$

x_i may also represent quadratic or other non-linear forms as long linearity in the parameters remains. The stage wise scores P_{ms} will often be obtained from surveys, which means that in due course background variables can be collected, so as to enable the logit function estimation later on. These logit functions can also assist in assessing improvements in the weather service chain as, if improvements can be linked to explanatory variables x_i.

The above decomposition analysis of effectiveness of information propagation in the weather service chain (WSCA) can be combined with various valuation methods.. Next to the so-called 'Cost-loss' approach seven other methods were identified that can be employed to assess the economic value of (increments in) weather information. Various methods can also be used in combinations, e.g. in the context of weather service chain analysis (WSCA). All in all the following approaches can be mentioned:

1. *Transport system simulation model*

2. *Questionnaire based survey*

3. *Natural experiment*

4. *Downscaling from retrospective macro-analysis*

5. *Simple changes in accident rates*

6. *Broader production function approach*

7. *Opportunity costs*

8. *Cost-Loss model*

3 APPLICATION OF WSCA TO ROAD WEATHER

3.1 Introduction

In Nurmi et al [19], in the framework of the FP7 EWENT project, the WSCA was applied among others to road transport in combination with a natural experiment based Cost-loss approach [1]. Vehicle drivers are a very heterogeneous group and they combine and use weather information with a great variation. Therefore it is impossible to create a simple decision making Cost-Loss model for vehicle drivers that would help to estimate the value of weather forecasts for different individuals on the road.

As a public-good the weather services don't have a market value. Non-market valuation methods could be used to estimate the aggregate value of weather services for the households, but it would be very difficult to estimate which part of the value is derived from the services aimed specifically at the vehicle drivers. A good example of such a study is found in [13] where the value of public weather services and possible improvements is estimated with a contingent valuation method. In the study the researchers divided respondents into two groups, distinguished by the time spent outdoors as estimated by the respondents. Lazo and Chestnut [13] found a statistically significant difference between the values that each group gave to weather forecasts. It could be possible to conduct a similar study where the respondents would be divided into groups based on the time they are travelling on the roads.

Other possible methods to evaluate the benefits of weather forecasts include natural experiments - where forecast events are compared to surprise events and the differences of responses are reported, and a valuation option where simple changes in accident rates are evaluated on the basis of expert opinions and the reduction in expected accidents is to be expressed in monetary terms. This approach was applied in combination with WSCA to assess the value of weather information for road users. The first step in our case study was to estimate the hypothetical maximum value of a perfect weather information system. To this end, we used data from the Finnish Motor Vehicles Insurer's Centre with all the road accidents recorded per day and by region from 2000 to 2009. We combined this data set with a data set from Finnish Meteorological Institute containing all the road weather warnings. We conducted a natural experiment to allow us to estimate the total costs of road accidents caused by adverse weather conditions.

As an indicator of the days without adverse weather, road weather warning was set at 1 on the actual day and on the evening before. We concluded that there were no cases in which days with poor or very poor driving conditions were not accompanied by issued warnings on the previous or same day. Also Sihvola et al. [8] noted that no such days were found in their study, where the weather had been poor or very poor but no warnings had been given. With this method, about half of the days in winter time were labelled as days with normal driving conditions, with the exact share varying over municipalities. As an average in the whole country, normal weather was estimated to occur on 48% of the days, poor weather 45% and very poor weather 7% of the days. Only days without road weather warnings on the day or evening before were accepted to ensure that adverse weather was not a factor in the accident rate we estimated to occur on normal conditions. With these settings, we estimated the average accident rate on days with normal driving conditions. We conclude that this is the average amount of road accidents per day in winter time for other reasons beside poor weather.

Next, the average accident rate on days with poor weather was calculated. A day was classified as having poor weather when at least one of the warning levels concerning the day or the evening before was at least 2. This is a rather conservative approach, implying that days are relatively easily classified as 'adverse weather day'.

We calculated the average accident rate for those 'adverse weather' days. The resulting average is our estimate of daily accident rate under adverse weather conditions. We also calculated the averages for days with "poor" and "very poor" weather warnings separately and found a statistically significant difference accident rate between these days. However, the analysis is done with calculations which include all poor weather days. The accident rates in any of the involved municipalities were significantly higher than on the days with normal weather conditions. Also the level of accidents without casualties had gone up much more than the rate of accidents with casualties. This is in line with the current theory. The resulting reduction in the traffic intensity and flow speed decreases the share of severe accidents, but slippery roads on the other hand increase the frequency of accidents [14]. The difference in accident rates between "normal weather days" and "poor weather days" is what we concluded to be the number of accidents that were caused by adverse weather conditions.

During a day with adverse weather there occurs in average 47 accidents more than on a day with normal road conditions. Of these incremental accidents 43 are without casualties while 4 involve casualties. The results imply that about 10% of all winter time accidents are caused by adverse weather conditions. Our findings are in line and confirm those of the Norwegian expert cited in [15].

3.2   Applying WSCA to Finnish road accidents

We should point out that the above number of incremental accidents is the realized increased accident rate on days with poor or very poor driving conditions. The number would be higher if some of the accidents had not already been mitigated with the help of road weather warnings and other weather information. As a conclusion, the increased accident rate is the reduction potential left for improved winter weather information to further reduce. Other accidents besides the accidents caused by adverse winter weather are out of scope of the winter weather information services as we know it. Possibly other types of (year round) weather services may help to reduce some of the other road accidents, but the greater part of these are linked to other factors such as alcohol use, local road conditions, etc.

The Finnish Transport Agency estimates that the average material damage for an accident without casualties is 2950 euros. The average cost of an accident with casualties is rated by the agency at 493000 euros. With these figures, we establish that the annual winter weather related accidents amount to calculatory losses of about 226 million euros given the current weather information services.

We estimated the approximate magnitudes of each of WSCA steps by a literature review. Some of these steps entail more uncertainty or might be more controversial than others. More study is needed – especially with respect to step 5 – how many people really have the ability (know-how) to create an effective response on the basis of the weather information they receive. The magnitude of each step is nothing more than our best estimate/guess to date (see table 1.). By putting these steps in a sequence and varying them, it's easy to see how improved levels on each step could create more value.

1.   accuracy – 92 %
2.   information/message customer orientation – 90 %
3.   access – 62 %
4.   comprehension – 85 %
5.   ability to respond – 40 %
6.   effectiveness of response – 80 %

When the potential maximum of weather information value is filtered through these steps, the cumulative share of the original value is lowered on each step. On the final step 6, only 14% of the potential value is reached.
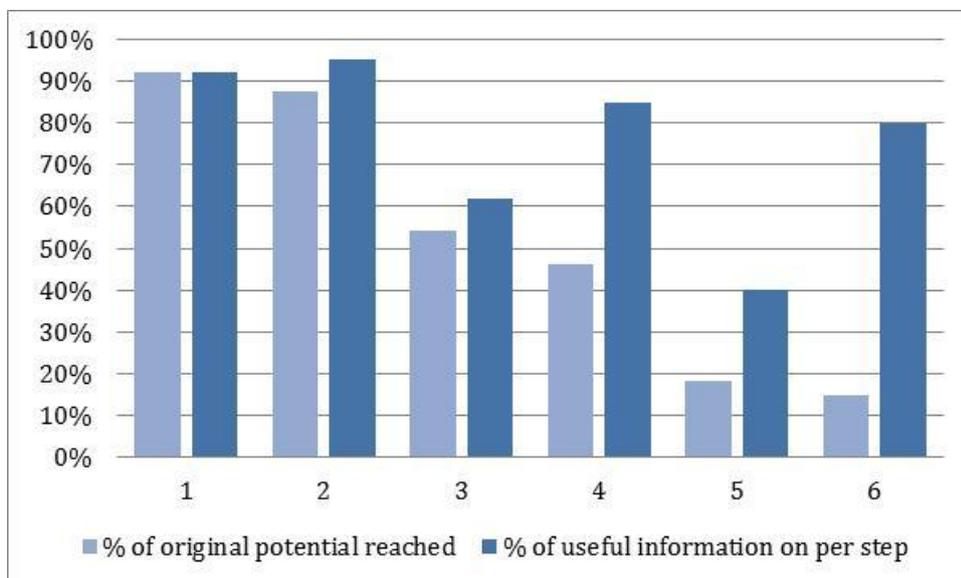

Figure 1. Responsiveness to weather information by a factor

Since we know that the current average value of road accidents is about 226 million euros per winter season and only 14 % of the potential damage reduction value is effectively addressed, we estimate that the current savings from weather information are 36 million euros per year.

$Accident\ costs\ with\ the\ current\ weather\ information$
$= X - 0.14\,X, where\ X\ is\ the\ estimate\ of\ accident\ costs\ without\ any\ weather\ information, X$
$= 262\ million\ euros$

$$Accident\ costs\ without\ weather\ information$$
$$-\ Accident\ costs\ with\ current\ level\ of\ weather\ information$$
$$=\ The\ value\ of\ weather\ information\ =\ 36\ million\ euros$$

By manipulating the steps, we notice for example that with 100 % accurate forecasts (leaving other factors untouched) the value of weather information would be about 39 million euros, which is 3 million euros higher than with the current level of accuracy. However, the accuracy rate could have an impact also on the drivers' response on the weather information, as the credibility of the information would be higher.

3.3   European level assessment

Palma and Rochat [16] studied the travel decisions made by vehicle drivers in Geneva with respect to weather information. A similar survey has also been made in Brussels [17]. The comparison of these results showed an overall similarity in the patterns for mode, route and departure time choices. Also the Finnish studies used in this paper [8; 9;12] exhibited a high degree of similarity with the aforementioned studies regarding the decisions made while weather information was received. This indicates that there exists a broad similarity in traveller's decision making behaviour across countries, at least at the European level. Although there might be some cultural differences, we believe that our estimates of the magnitude of each step in WSCA are capable of giving good estimates at the European level as well.

In the tentative benefit-analysis below a 10 % accident ratio (as being closely weather related) will be used. This is in line with the findings in this report, which are also corroborated by other studies [15]. With these assumptions the total welfare lost from road accidents in Europe would amount to 20.7 billion euros a year as indicated in the EWENT WP4 reports [15; 18]. Without any weather information, we estimate that accident costs would be about 24.1 billion Euros, which is 3.4 billion euros (i.e. 14%) above the current cost level. This amounts to the estimate of the value of the current road weather information in Europe. The hypothetical 100 % accurate weather forecasts could raise the benefits by 241 million euros (but improving other parts in the chain as well would raise the leverage of forecast improvements tremendously).

$$Accident\ costs\ with\ the\ current\ weather\ information$$
$$=\ X - 0.14\ X, where\ X\ is\ the\ estimate\ of\ accident\ costs\ without\ any\ weather\ information, X$$
$$=\ 24\ 098\ 822\ 000\ euros$$

$$Accident\ costs\ without\ weather\ information$$
$$-\ Accident\ costs\ with\ current\ level\ of\ weather\ information$$
$$=\ The\ value\ of\ weather\ information\ =\ 3.4\ billion\ euros$$

4   CONCLUSIONS

The road transportation sector can be divided into three sub-groups: 1) vehicle drivers, 2) bus and trucking operations and 3) infrastructure maintenance operators. Vehicle drivers use public weather information (such as Finnish Road weather service) to make better pre-trip decisions. These decisions include destination, mode, route and departure time choices. Choices are made to lower the risk of accidents or to ensure arrival in time. Bus and truck operations are more professional in the use of information, but require longer lead-times which would allow them to reschedule, reroute, postpone or find safe-haven for vehicles or cargoes. Furthermore, last minute changes in committed delivery schedules risk raising the cost, owing to contractual penalty charges and/or future reduction in demand as a result of diminished customer satisfaction. The use of weather information is crucial especially for winter road maintenance. The benefits of accurate weather forecasts include effective use of personnel and chemicals, and timely respond to weather events to ensure a minimum level of service. Literature review suggests that the benefits of weather information are much higher than the costs for winter road maintenance.

The value of the current level of weather information for Finnish vehicle drivers was estimated at about 36 million euros per year, by applying WCSA. These benefits include only the reduced level of accidents. Improvement of some other steps in the value chain than (only) weather service accuracy (such as 'better maintained access' and 'ability to respond') would greatly enhance the leverage effect of investments in forecast improvement. An even more tentative use of the same approach for Europe as a whole resulted in an estimated benefit generated by weather services for road users in Europe of approximately 3.4 billion euros per year.

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