Extreme weather impacts on European networks of transport

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Executive summary

Setting the stage

It is obvious that weather affects production and consumption activities in society. Unfavourable weather conditions will often raise production cost, not the least in transport, and lower the net benefits of many consumer activities. Yet, to assess these impacts quantitatively requires rather diverse, accurate and jointly usable data. So far, quantitative assessment of the impacts of weather conditions has been piecemeal with a lot of ‘black spots’ and large variations in precision across EU member countries. Furthermore, the actual question discussed in this report is what would be the economic value of an increment in the weather service level as compared to the current level of service provision.

There are quite marked differences in the forecasting capability of different weather phenomena and variables, including those leading to extreme, adverse, or high-impact, weather conditions. However, looking at past historical forecast performance, there is a definite positive trend in the forecasting capabilities, whatever the weather quantity or phenomenon. The improvement in forecast quality has been shown to be more or a less steady increase of one day per decade. Therefore, we are building on a similar trend to continue, i.e. expecting the usefulness of final weather forecasts to increase by one day per decade until the foreseeable future. This idea is utilized to support our value assessments of weather services on different transport modes.

Weather can affect economic production directly, implying changes in the production cost or revenues and in some cases causing loss of capital due to physical damage. Weather can also have an impact on household consumption. People for example buy clothes depending on the (expected) weather. Weather can also affect many sectors indirectly, e.g. when weather affects the capacity or demand of some transportation modes and consequently a part of the users decides to switch to a less affected transport mode. The EWENT study is specifically concerned with the effects of extreme weather conditions on different transport sectors and modes. In contrast to other weather conditions, the direct effects of weather extremes are usually only negative, leaving the particularly weather sensitive markets upset.

Weather information enables better decisions by the various decision makers, i.e. travellers, transport service operators, and infrastructure owners. The resulting better preparedness and better informed decisions attenuate extreme weather induced cost and price effects, which is in principle a common benefit for all market parties. In this respect it merits to emphasize that adequate weather and climate information affects short term (operational) decision making in transport (reducing acute risks), as well as long term (strategic) decision making on investments and maintenance cycles (improving the system’s coping range).

For technical and regulatory reasons service supply in public transport systems and capacity of all transport infrastructures are entirely fixed in the (ultra)short term. As a consequence the obstructions and capacity constraints caused by extreme weather events lead to either very high (momentary) prices or to indiscriminate rationing and congestion. So, users are economically and possibly socially harmed either by an economic crowding out caused by high prices or by severe congestion and queuing. Better service provision of weather information alleviates the inflexibility problem in infrastructure.
Establishing the value of weather information

The attributed value of (incremental) weather information depends on the difference it makes on the outcomes of a company or sector (balance of changes in costs and revenues). Since both the weather information and the generation of eventual benefits is at least to some extent uncertain, the decision maker has to deal with expected values of changed costs and revenues. Furthermore, if the economic utilization of weather information requires some investments (implying that the benefits build up over time during a sequence of extreme events), it concerns the expected values of discounted flows of changed costs and revenues.

To support the decision makers in this kind of analysis often a so-called Cost-loss model is proposed. In the model, taking protecting actions involves certain costs while no protection at all is expected to result in larger losses if adverse weather conditions indeed occur as forecast. The optimal decision whether to protect or not is influenced by prior knowledge of weather conditions. The weather information provider delivers this information and it can be shown that the better the quality of the forecast the greater the expected value of the decision. This model can be further developed to include the attitude towards risk of the decision maker.

In traditional Cost-loss method it is assumed that all involved actors are perfectly informed, perfectly knowledgeable about options, and perfectly rational. For most user groups this is usually not the case as is shown in chapters 4 and 6, and therefore additional analysis is necessary in particular about the extent to which imperfections in information use lead to inaction. To this end weather service chain analysis is introduced.

Attribution of cost reductions related to coping with adverse weather conditions in transport to particular improvements in weather services is in most cases – in principle – possible. However, one should allow for – sometimes considerable – uncertainty ranges in estimated benefits. The apparent coping range often also changes due to other developments in technology, traffic regulation, changes in habits and norms, evolution in forecast skill distributions, etc.

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. Simple Cost-Loss model

No single methodology could handle the estimation of the benefits for all different transportation sectors or modes. The selection of methods depends on the available data and the transport
mode in question. Each transport sector and mode uses meteorological information in different ways and for answering different questions.

**Weather Service Chain Analysis**

The significance of differences in the ability to communicate and use the weather information can be illustrated by means of *weather service chain analysis* (WSCA). WSCA considers seven filters which forecast services are passing through the entire chain from 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 realize. The stages are:

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

The more professional and meteorologically skilled the end-user is the lesser the filters affect the attainable value added generated by the use of weather services. Therefore better accuracy and lead-time of weather forecasts might create value just from these improvements of the prediction part. As regards transportation these users might include decision-makers in aviation and marine navigation industries. On the other hand for some road users (non-professional traffic modes) the significance and improvement potential of these steps will weigh more. Therefore, the stages can be studied to an extent appropriate for the traffic mode under consideration. The above seven 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.

**Characteristics of different transport modes in relation to weather information use**

Without meteorological services there could not be any commercial aviation at the scale as we know it nowadays. For this reason there is no point in calculating the total value of weather information for the industry. On the other hand an incremental improvement of the current aviation weather service level can be assessed. With more accurate forecasts costs of unnecessary precautionary measures and weather related delays and cancellations could be avoided. Another important feature to consider is the knock-on effect in a complex network of flights. One delay can potentially create a multiple number of subsequent delays. The benefits of avoiding one (initial) delay are then larger than the direct costs of that particular (initial) delay.
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 resulting from 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.

One of the least studied sectors with respect to weather information utilisation is rail transport. To enable the project researchers to use WSCA an interview with the operative managers of the Finnish transport agency (section rail network maintenance) was conducted. The bottleneck turned out to be step 4 of the WSCA as the decision makers did not adequately understand crucial parts of the weather forecast information. As a consequence the level of utilisation of weather information remains low and thereby leads easily to delays in train services under adverse weather conditions. Delays are a considerable burden for train service users, because lack of competition and alternatives may prevent them from switching to another operator or to another mode. All in all incurred cost of adverse weather effects for railway services seem to be generally lower than those for other transport modes, but (regional) exceptions may exist. In this respect it is also worthwhile mentioning that based on the literature review and the interviews a preliminary conclusion can be drawn that public transport companies (as distinct from public transport authorities) tend to perceive economic risks of adverse weather conditions predominantly in terms of the costs to their own companies (extra repair, extra fuel, a dip in sales). The incurred losses for travellers (time cost and other cost of delays and cancellations) seem to be generally overlooked by those actors.

Another often ignored transport mode is non-motorised traffic (pedestrians and bikers). The costs of tripping and slipping are truly substantial, especially in Nordic countries. For example, the estimate for Finland is 2.4 billion euro per year (including cost of temporary and permanently lost working hours). Tailored weather information has the potential to be highly beneficial in the reduction of these costs. Part of the benefits are realized through better service level in maintenance and part from more informed decisions of pedestrian and cyclists. These decisions include the right choice of footwear or tires for the cyclists, timing of the trip, route choice, mode choice and time of departure.

Application of valuation methods and crude estimates of realized and potential benefits

To illustrate the use of WSCA and the other valuation methods, three case studies were conducted. In the first case study data from the Finnish Motor Vehicles Insurer’s Centre were used, encompassing all the road accidents recorded per day and by region from 2000 to 2009. By casting the question as a natural experiment the – traffic intensity normalized – number of
accidents on an average day was compared between days with adverse weather conditions and those without such conditions. On each day with adverse weather conditions there are on average 47 more accidents. About 10 % of all winter time accidents are thus caused by adverse weather conditions. These findings are in line with study results from Norway and other countries. The consequent monetary value of the accidents caused by adverse weather was calculated while using the damage valuation guideline data of the Finnish Transport Agency. The annual weather related accident costs are estimated at approximately 226 million euros per year in Finland in the recent past.

Subsequently, the WSCA was applied to these outcomes. The ratings of the subsequent stages was based various existing (survey) studies. When the potential maximum of weather information value is filtered through each step, the cumulative share of 14 % of the potential value is reached. As the current average level of road accidents is 226 million euros and only 14 % of the potential value is reached, the current savings from weather information would amount to about 36 million euros per year. Literature review suggests an overall similarity in patterns for mode, route and departure time choices in Europe. The EWENT Deliverable D4.3 by Nokkala and Kreuz (2011) calculated that if 10 % of road accidents are caused by adverse weather, this would translate to a monetary value of accidents of around 20.7 billion euros a year. Without any weather information, we estimate that these costs would be about 24.1 billion euros or 3.4 billion euros more compared to the current level, but this should be understood as a crude estimate.

Case study 2 included an interview with the operative managers of the Finnish Transport Agency. The Finnish Transport Agency is responsible for the management, development and maintenance of the Finnish railway network. With the results of the interview, we evaluated each step of the WSCA and concluded that only about 20 % of the potential value of weather information is actually perceived. The delays in rail traffic cause travel time losses to travellers, in Finland 2010 these amounted to 5.6 million euros. We estimate that without any weather information the delay costs would be around 7 million euros and the value of current weather information to be about 1.4 million euros in Finland. Crude estimates in Europe level would suggest benefits from 50 million to 130 million euros.

The value of improved weather information for aviation was assessed in case study 3, relying on Eurocontrol statistics. From the statistics we inferred the estimated costs of weather related delay costs hovered between 326 million euros and 453 million euros. We added the costs of flight cancellations and found out that, on average, the combined costs of weather induced delays and cancellations had been close to 700 million euros per year. A study by Klein et al. 2009 estimated that 40 % of delays could be avoided with weather information improvements. This would add up to 280 million euros of avoidable costs per year in Europe. Further benefits would arise world-wide due to network effect of flight-delays.
Table S1. Summary of the results of the case studies

<table>
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<tr>
<th>Transport mode</th>
<th>Estimated value of benefits in Finland</th>
<th>Estimated value of benefits in Europe</th>
<th>Estimate of potential value of improved weather information</th>
<th>Used Valuation methods</th>
<th>Included benefits</th>
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<td>Vehicle drivers</td>
<td>36 million euros</td>
<td>3.4 billion euros</td>
<td>can be calculated for each step in WSCA</td>
<td>natural experiment, WSCA</td>
<td>reduced accident costs</td>
</tr>
<tr>
<td>Rail transport</td>
<td>1.4 million euros</td>
<td>50-130 million euros</td>
<td>can be calculated for each step in WSCA</td>
<td>expert interviews, WSCA</td>
<td>travel time savings</td>
</tr>
<tr>
<td>Aviation</td>
<td>-</td>
<td>-</td>
<td>280 million euros</td>
<td>statistics + literature review</td>
<td>reduced delay &amp; cancellation costs</td>
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1. Introduction

This report discusses economic implications of weather conditions for transport and more in particular it considers the economic valuation of weather information for transport systems, with special emphasis on extreme weather circumstances. The report is a contribution to Work Package 5 (WP5) of the EWENT project. WP5 deals with risk management of weather related risks of transport systems.

The purpose of this report is to survey alternative approaches for assessment of economic effects of weather information services for transport systems in terms of their applicability, prerequisites, and type and quality of results. Also a few illustrative calculations of economic impacts of specific weather services will be made. The output of this report can be used in other steps of WP5 as well in other WPs, notably with respect to judging priority setting of transport safety policy issues and research policy (sub)themes. In addition the output will be helpful for studies that aim to valuate existing or envisaged weather services for the transport sector, as well as to obtain an indication of the overall macro-economic significance of weather services for the transport sector.

It is obvious that weather affects production and consumption activities in society. Unfavourable weather conditions will often raise production cost, not the least in transport, and lower the net benefits of many consumer activities. Yet, to assess these impacts quantitatively requires rather diverse, accurate and jointly usable data. So far, quantitative assessment of the impacts of weather conditions has been piecemeal with a lot of ‘black spots’ and large variations in precision across EU member countries. Furthermore, the ultimate question is what would be the economic value of an increment in the weather service level as compared to the current level of service provision. This requires understanding of the contribution of weather information in decision making by producers and consumers and of the extent of non-linearity in these contributions in relation to the amount of weather services delivered. In this respect, and with reference to overall risk management in transport, it should also be realized that other preventive actions, such as adaptation in pavement, tires, and traffic signalling, may be cost-effective as well and their implementation may decisively reduce the net benefits of enhanced weather services.

The structure of the report is as follows: Chapter 2 presents the theoretical framework for the effects of extreme weather events on production and consumption. First these effects are considered in general and subsequently the particular features of transport markets (such as travel time & mode substitution and rigid supply) are taken into account. It is then explained how weather information can mitigate these adverse impacts of weather extremes. In chapter 3 the methodology and theoretical underpinning of valuating the incremental benefit of a weather services are discussed. First, the so far often used Cost-loss model is introduced to illustrate how individual decision-makers (can) use weather information and how the value is composed for a single decision-maker. Subsequently, uncertainty and incomplete information are introduced centred around the concept of weather service chain analysis, which also links micro and macro level approaches.

Each transport sector and mode uses meteorological information with different ways and for different purposes. Chapter 4 gives a description of each mode regarding their weather
information requirements, usage, effectiveness and goals. A thorough literature review is conducted to identify suitable methods to estimate the value of weather forecasts for different transport modes and sectors. Chapter 5 gives a listing of these methods and examples of available value estimates. In chapter 6 we illustrate how these methods can be applied and used in combinations e.g. in the context of WSCA. We are able to give crude estimates of the weather information value for different sectors of transportation in Europe.
2. Weather effects on production and consumption

2.1. Introduction

Practically in all economic sectors production is directly or indirectly affected by weather. For example, harvests may be destroyed by a hail storm, the aviation industry may be exposed to heavy losses because of weather related delays, and just as well the financial sector is affected inter alia via large pay-outs due to weather related insured damage and through ups and down in the markets for weather derivatives. Next to production, weather has also impacts on household consumption. People buy clothes depending on the weather conditions, may change their minds regarding indoor or outdoor leisure depending on the weather, choose to use the train instead of driving by own car or take a vacation somewhere warm and sunny instead of a domestic location.

According to Larsen (2006) a sector is economically sensitive to weather if weather adversely (or beneficially) affects the behaviour or output of an economic sector either directly or indirectly. An indiscriminate application of this definition would define all sectors as 'weather sensitive'. Lazo et al (2006) analysed weather sensitivity of the US economy (in terms of GDP by state/sector) regarding high and low temperatures, annual precipitation and annual variation in precipitation. In fact that analysis shows that indeed all sectors are sensitive, though to a different degree and to different features of the weather. Agriculture and mining stand out, whereas the finance & insurance industry comes third. The transport sector (in the US) would be only moderately sensitive according to the 2006 study. At first glance this result may seem surprising, however it should be realized that extreme weather events were not included in the analysis. Furthermore, in developed economies basic infrastructure, such as for transport and energy, tends to have a large coping range, since the society should trust that these systems also remain functioning in less favourable conditions. As a consequence a significant part of the potential sensitivity does not become apparent thanks to counter measures (weather services, road maintenance, traffic signalling, etc.).

Leviäkangas et al. (2007) indeed find for Finland that the economic value of weather services for transport are significant, not only in absolute sense, but also in comparison to the value added of the sector (~5%, excl. warehousing). To this could be added that none of the above cited studies has assessed macro-economic effects of weather and or weather services, as interaction effects between sectors and implications for labour markets were not analysed. In Perrels et al (2011) is indicated that the eventual cumulated impacts of extreme weather events on regional and national value added are usually appreciably larger than the initial damage.

1 48 states, 11 sectors, 24 years (1977-2000); a translog function with capital, labour, energy and weather indicators (HDD, CDD, annual precipitation, variation in annual precipitation); several estimation approaches (levels, AR(1), state fixed effects); extreme weather impacts not included (hurricanes, tornadoes, etc.); the estimated model is used to calculate weather induced output variations for the period 1931-2000.

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In some cases the same phenomena can have an adverse effect on one sector and a positive effect on another: a nice hot summer could make people travel more to the countryside and spend less time in the city. Therefore the aggregate economic effect of a weather phenomenon for the whole society cannot be evaluated just by focusing on a single sector.

Weather can affect a sector directly, implying changes in the (unit-)cost of production and in extreme cases causing physical damage (loss of capital stock). Weather can just as well have indirect effects on a sector, e.g. when weather impacts on production costs (and prices) of other sectors and/or on the demand levels of other sectors. For example, in Nordic countries protracted lack of precipitation or a significant cold spell raise the cost of electricity production. With some delay this would increase the operational cost of train services. During holidays bad weather will cause consumers not only to travel less, but also to select other destinations (urban) than in good weather conditions (countryside and urban rim). The changes in the demand for free-time activities in turn imply changes in the modal split and spatial distribution of demand for transport.

The EWENT study is specifically concerned with extreme weather conditions. This means that as regards cost effects, prevention and mitigation measures can raise the unit-cost of production (and of consumption, assuming that extra production costs are added to end-user prices). In as far as prevention and mitigation turn out to be insufficient damage cost will arise, whereas in case of reduced capacity (due to either damage or prevention) prices and/or queuing cost (extra travel time) will go up. Consumers can also be confronted with extra cost induced by extreme weather regarding their own activities (e.g. when travelling by own car or by bike). In addition, besides causing tangible (monetary) extra cost bad weather may reduce the utility of travelling, i.e. by experiencing less fun and more anxiety. In as far as reduced utility of travelling incites consumers to switch mode or reschedule a trip, the extra cost of the rearrangement can be assumed to be lower than the shadow price of the (originally) reduced utility. Consequently, in a cost-benefit analysis the reduced utility effect should only be accounted for with respect to non-rearranged trips.

As emphasized in the last example, but also implied by the previous ones, the quantification of the economic impacts of weather events is tricky. Especially when more comprehensive assessments are desired, double counting and deficiencies related to indirect effects can easily occur. For this reason the next section discuss in more detail effects and responses in production (2.2) and (household) consumption (2.3), in general terms and more specifically for transport (2.3 & 2.4).

2.2. Production

Production in economics means the combination of capital (land, buildings, equipment), labour (and embodied knowledge), and energy and materials with the purpose to produce commodities or services that can be sold on the market against a price, which enables the continuation of production (i.e. implying cost coverage + accounting for future investment needs and a risk
premium for the entrepreneur). For some public goods no prices are (or even cannot be) charged, such as is the case for many public weather services.

Weather conditions affect the efficiency of production processes as well as the quality and/or price of inputs. Thereby weather is a kind of an indirect input. Yet, weather cannot be optimally selected by decision makers to maximize profits. Firms are forced to adapt to weather uncertainty by using climatological information or weather forecasts. How firms can use weather forecasts in their decision-making process is explained in chapter 3. In this section is explained graphically how weather affects production, costs, and thereby market prices and volumes.

In an orthogonal projection volumes supplied and volumes sold on a market are indicated on the x-axis, whereas prices are indicated on the y-axis. The supply curve shows the relation between the price and quantity that producers are willing to supply. The default assumption is the higher the price, the more firms will supply. This is illustrated in figure 2.1, where supply curve S₀ represents the situation in absence of an extreme weather event. Let's assume that the supplier(s) provide a quantity Q₀ to the market as they assume this would just exhaust demand at an (acceptable) price p₀. When an extreme weather event occurs achievable production capacity is reduced, whereas production costs per unit of product may go up. The capacity constraint is represented by a leftward shift of the supply curve, implying that any quantity is supplied at higher prices than before. Furthermore, the higher unit-cost (assuming a percentage increase) cause a rise in the slope of the supply curve. Both effects are included in the new supply curve S₁.

The initial (immediate) effect could be a reduction of supply to Q₁. Due to regulations (such as for public transport tariffs) or incomplete information the price may initially remain the same (p₀). However, that would probably mean that not all demand is satisfied (the demand side will be added to the graphs in next steps). As a consequence prices and supplied quantities will rise (following S₁). The other extreme would be that the suppliers would still be capable to produce Q₀, but in the new circumstances they would charge a price p₁ at that output level. It is however unlikely that all (original) clients would be willing to pay that price. Consequently, a new price somewhere between p₀ and p₁, and a new quantity, somewhere between Q₀ and Q₁ will occur. Improvement of weather services (e.g. enhanced early warning) would for example mean that most of the damage can be prevented, this would mean the supply curve would not any more shift, but only the slope would rise. In figure 2.1 this is illustrated by supply curve S₁*. Obviously the price and quantity impacts would be much smaller in that case. In other words the market would be less ‘upset’.

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² This is an intentionally generic definition. Decision making guidelines of producers can be further focused, e.g. profit maximizing (at various time scales), maximizing market share, preventing entry of new competitors (through pricing), etc.

³ In particular when there prevails non-exclusion in consumption (i.e. the volume of consumption has no or barely impact on the production cost), and a fortiori when increments in consumption are hard to observe, market prices cannot be charged. Nevertheless, in some cases a kind of (annual) fee may be charged, in order to achieve (partial) cost coverage and prevent a rise of the general public budget (and taxes). If need be there are several methods to infer a shadow price of public goods.

⁴ If there is more than one supplier of the same type of product, it is assumed that their production functions (and hence supply curves) are essentially the same.
The above explanation alluded to some extent to differences in time frames (initial and follow up responses), but in the case of transport services it is quite important to distinguish between ultra-short term, short term, medium term and long term. For example both for technical and regulatory reasons supply in public transport is entirely fixed in the (ultra)short term. The consequences are shown in figure 2.2. The nomenclature is the same as for figure 2.1. From the figure can be inferred that an immediate reduction in supply may cause congestion if demand appears to be much less sensitive. This is for example the case for air travel. In that case consumers either ‘pay’ extra due to queuing (extra travel time) or pay higher fare prices to avoid delays. It also is clear that better weather services would have a dramatic effect on the reduction of market turmoil (curve $S_1^*$ instead of $S_1$).
Production can be described in a mathematical way by means of production functions. Output, such as the flights that an airline offers, can be related to the level of inputs the airline uses:

\[ Q = f(X_1, X_2, X_3, \ldots, X_n) \]

where \( Q \) is the quantity of output and \( X_1, X_2, X_3, \ldots, X_n \) denote quantities of factor inputs (capital, labor, energy and materials). There are several classes of production functions. A fairly common type, often used in applied general equilibrium models, is the constant elasticity of substitution (CES) production function of which a subset is the Cobb-Douglas production function.

\[ Q = A[\delta K^{-\rho} + (1 - \delta) L^{-\rho}]^{-1/\rho} \quad [2.1] \]

where \( Q \) denotes total production, \( L \) labour input, \( K \) capital input, \( A \) a total factor productivity parameter (representing technical efficiency), \( \delta \) relates to the factor share in the technology mix and \( \rho \) the substitution elasticity (between production factors \( K \) and \( L \)). Conditions are \( 0 < \delta < 1 \) and \( \rho > -1 \) (and \( \neq 0 \)).

If more production factors are to be distinguished a nested set-up is necessary, e.g. solving the mix between capital and energy at one level and the mix of labour and the capital-energy composite at another (higher) level. In case a Cobb-Douglas function is used more production factors can be distinguished simultaneously.

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5. Production functions can be denoted in volume terms (the quantities of inputs and output) and in value terms (quantities x prices). The quantity option usually requires the use of numeraires.

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Weather conditions can be accounted for in several ways. The total factor productivity parameter $A$ could be elaborated to allow for significant deviation from average weather conditions, denoting an achievable production level which deviates from the one under normal conditions. Furthermore, in case of extreme weather phenomena that are likely to cause damage to the capital stock, variable $K$ could be corrected. In this way for example a three tier production function could be proposed.

Under weather conditions, where none of the key weather parameters deviates significantly from the average, the default CES function prevails:

$$Q = A[\delta K^{-\rho} + (1 - \delta)L^{-\rho}]^{-1/\rho}$$  \[2.2\]

Under extreme yet non-disastrous weather conditions, where at least one key weather parameter deviates so much from the average that it noticeably affects production conditions, the total factor productivity is corrected for the effect at hand:

$$Q = Ae^{w_i}[\delta K^{-\rho} + (1 - \delta)L^{-\rho}]^{-1/\rho}$$  \[2.3\]

where $w_i$ is the applicable parameter value for extreme weather event of type $i$ and $w_i \leq 0$

Under extreme yet non-disastrous weather conditions, where at least one key weather parameter deviates so much from the average that it noticeably affects production conditions, the total factor productivity is corrected for the effect at hand:

- **during** the extreme weather condition, but after (permanent) damage occurred:

  $$Q = Ae^{w_i}[\delta (1 - q_{w_i})K^{-\rho} + (1 - \delta)L^{-\rho}]^{-1/\rho}$$  \[2.4a\]

- **after** the extreme weather conditions subsided, while permanent damage occurred:

  $$Q = A[\delta (1 - q_{w_i})K^{-\rho} + (1 - \delta)L^{-\rho}]^{-1/\rho}$$  \[2.4b\]

where $q_{w_i}$ is the estimated share of the capital stock unfit for production as a result of an extreme weather event of type $i$ and $0 \leq q_{w_i} \leq 1$.

The impact of the extreme weather condition can subsequently be assessed by analysing the shift in $Q$, i.e. $\Delta Q$, by taking the differences between the alternative formulation of $Q$ as explained above.
2.3. **Household consumption**

Household consumption in economics means the acquisition of goods and services by a household with the purpose of fulfilling the needs of the considered household (food, housing, mobility, clothing, etc.). The conjecture is that a consumer has a utility function on the basis of which the utility of each (incremental) good or service can be established given a monetary budget constraint.

The utility function of a consumer is an expression of how preferences over different consumption bundles are organised and rated, and consequently on the basis of the function can be inferred how changes in the budget and/or prices will affect the amounts purchased. Utility depends on the amount (and quality) of goods that the consumer has to her disposition so that

\[
Max(U) = Max(f(x_1, x_2, ..., x_n)) \tag{2.5}
\]

The consumer’s problem is to maximize her/his utility \(U\) with the budget constraint

\[
y = x_1p_1 + x_2p_2 + ... + x_np_n, \tag{2.6}
\]

where \(y\) denotes consumer’s income, \(x_i\) the amount of a good and \(p_i\) the price of a good \(i\).

Depending on the type of utility function and the variety of attributes to be taken into account various demand functions can result (see Annex A). Similarly as mentioned for production functions demand can be expressed either in value terms (quantity times price) or in volume terms (quantity). In transport demand modelling there is a tendency to express demand in volume terms (number of trips, passengers, etc.) due to the need to link back to physical descriptions of the system (capacity).

\[
Q_{mt} = f(x_1, ..., x_n; p_1, ..., p_n; z_1, ..., z_n) \tag{2.7}
\]

where \(x_i\), \(p_i\), and \(z_i\) denote quantities of available alternative travel modes, the prices of these modes, and the quality features of these modes respectively. The last variable \(z_i\) may in fact represent a bundle of features (e.g. safety, accuracy, tidiness, etc.).

Traditionally demand curves show the relation between the price of a good \(x\) and the quantity demanded of the good \(x\). For a given curve other factors are held constant, including preferences, income and prices of other goods. Movement along a demand curve reports the change in the

---

\(\text{6 The basic model introduced here can be extended in several ways. For example, in a next section time use and time budget restrictions will be supplemented to this model, as time use (and time savings) are a key ingredient of transport economics. Furthermore, decision making among members of a household, long term aspects (purchase of durables, lifecycle models, etc.), hedonic models (Lancaster) and production-consumption approaches (home economics) will be left largely untouched. Some elements will be used in connection travel demand modeling. We also refrain from elaborating on the preceding decision, the share of income saved (not consumed) in the considered period.} \)

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quantity of $x$ demanded as the price of good $x$ changes. The change in the price is an endogenous change. Change of location of a curve occurs when at least one element of the exogenous factors (income, tastes, non-price attributes of the good, prices of another good) is changed. Both types of movements (along curve and relocation) are shown in figure 2. The price of good $x$ rises from $p_o$ to $p_1$, which is an endogenous change in the model. The new demand level for good $x$ is found by moving along the same demand curve $D_1$. Quantity demanded decreases from $Q_o$ to $Q_1$. This movement is represented by the blue arrow.

If any of the other relevant factors change, the demand curve relocates, in which case we have to draw a new demand curve to represent the new demand. We call this an exogenous change. For example a decrease in income, a reduction in the price of good $x_2$ (e.g. of a competing transport mode) or deterioration of the quality of good $x_1$ (e.g. crowded capacity or less predictable travel time) would result in a leftward shift in the demand curve. This shift is represented by the black arrow as lesser amount of good $x$ is demanded at any given price.

**Figure 2.3** Endogenous and exogenous changes in the demand curve

The slope of the demand curve is the marginal benefit of consumption of good $x$ on each quantity demanded and the total area under the curve is the total benefit of consumption. The reason why both endogenous and exogenous changes were included in the analysis is that extreme weather events can have both of these effects on the consumption. If the price of the good $x$ is increased due to extreme weather event, a movement along the demand curve occurs – labelled by the blue arrow. Similarly, if vulnerability reduction (per standardized trip) for mode 1 is more expensive than for mode 2 travel cost for mode 1 will rise more than for mode 2 and consequently demand adapts. If the utility of consuming $x$ is lower on each quantity, e.g. because bad weather reduces travel convenience and travel time predictability, the demand curve shifts to a lower level – depicted by the black arrow in figure 2.3.
In transport demand modelling the time use (trip duration), but also loss risks are often integrated into one compound cost concept, the so-called ‘generalised transport cost’. As a consequence the overall price of road transport is not simply a fare to be paid, but instead the price contains all the other costs involved in obtaining the transport service. Traditionally the time costs are held the most important of these costs and in transport economics the travel time is included in the price of the service. (Hensher and Brewer 2001). Because extreme weather events definitely have an effect on the travel time by reduced individual and flow speeds (see chapter 4.2.1), a movement along the demand curve takes place as the cost of driving rises. Extreme weather also decreases the utility of driving by increasing the accident risk and making the road conditions more stressful for an individual driver so that less utility is get from the driving. Thus, the demand curve shifts left and less road transport is demanded on each price level.

2.3.1. Travel time in the consumption function

Just like a monetary budget consumers have also a time budget, which affects demand in a similar same way as scarce money resources. So time should be included in the utility and demand functions, in particular in case of demand for passenger transport. Yet, time has even several qualities. Time is an important input in consumption activities, but is also a factor in production activity. Thus, time can be viewed as a commodity (i.e. ‘buying free time by sacrificing paid labour hours’), but just as well time is a means of consumption (mostly one needs at least some time to consume something) and an attribute of consumption (sufficient time may raise the enjoyment of consumption of good, too much may cause boredom and too little a harried feeling). As a generic (non-work) commodity, it is not irrelevant in which activity time is consumed. In that status its shadow price is the relevant wage rate of a particular (or the average) consumer.

DeSerpa (1971) elaborated the original Becker model on home economics by introducing the notion of (technically induced) minimum time requirements for each consumption activity. It is important to understand that consumption is in this case understood as a two stage process. First, in the current or previous periods goods $x_1, ..., x_n$ are bought, which together with the use of time are consumed at a certain pace to produce a final ready-to-consume service $Z_i$ (being a cup of warm tea or a car trip from A to B or whatever).

$$Z_i = f_i(x_i; T_i) \text{ \ where } i = 1 ... n$$  \[2.8\]

Utility is derived from consumption through the enjoyment of the ready-to-consume services $Z_i$, which in turn depend on adequate input mixes of $x_i$ and $T_i$, and therefore the utility function is reformulated as:

$$U = U(Z_1, ..., Z_n) = U(f(x_1, ..., x_n; T_1, ..., T_n))$$  \[2.9\]

For most consumers daily life implies that their paid labour time per week is fixed, at least in the short to medium turn. As a consequence their disposable income level is also (almost) fixed. This means that the budget constraint remains simple as in the previous section, all disposable income is spent:

$$y = \sum p_i x_i \text{ \ for } i = 1 ... n$$  \[2.10\]
Similarly there is also an obvious upper limit to the time allocated to different consumption activities:

\[ \sum^n_i T_i \leq T_o \]  

where \( T_o \) represents the daily or weekly time budget net of paid labour.

A consumer can decide to spend the minimal technically possible amount of time to generate and consume \( Z_i \) or to spend more than the minimum amount of time. DeSerpa (1971) formulates this by expressing the time requirement in relation to the intensity of use of goods:

\[ T_i a_i x_i, \text{ for } i = 1, ..., n \]  

Please note that the right hand side could also be a collection of goods instead of one good, but that does not affect the essence of the analysis. The inclination to spend more than the minimum of time required will depend on the extent to which the activity is regarded as an enjoyable activity, on the overall time pressure of the consumer, on the disposable goods (technology level, quality, price), on the skill of the consumer, and on external conditions – such as weather conditions – affecting the smooth progress of the process. In eq. 2.12 weather circumstances can affect both the overall inclination to minimise time use and the efficiency with which the goods can be used:

\[ T_{wi} a_{wi} x_i, \text{ for } i = 1, ..., n \]  

where the subscript \( w \) refers to the weather conditions, e.g. being either acceptable \( (w = 1) \) or adverse \( (w = 2) \). We may assume that \( a_{2i} \geq a_{1i} \). Eq. 2.13 could now also be split for acceptable and adverse weather situations:

for \( w = 1 \)

\[ T_{1i} a_{1i} x_i, \text{ for } i = 1, ..., n \]  

for \( w = 2 \)

\[ T_{2i} - a_{2i} x_i = 0, \text{ for } i = 1, ..., n \]  

Now the Lagrangian for the optimising consumer is reformulated as follows:

\[ L = U\left(f(x_1, ..., x_n, T_1, ..., T_n)\right) + \mu(T_o - \sum T_i) + \lambda \left( y - \sum x_i p_i \right) + \sum \kappa_i \left( T_i - a_i x_i \right) \]  

where \( \kappa_i \geq 0 \) \( (i = 1, ..., n) \), \( \mu > 0, \lambda > 0 \). \( \mu \) and \( \lambda \) reflect the marginal utility of purchasing power (disposable income) and time respectively, while \( \kappa_i \) is a parameter correcting the marginal utility of time in case of activities that are carried out at or within the minimum time bound. We obtain the first two conditions with the partial derivatives of the Lagrangian of the variables \( x_i \) and \( T_i \):
The next condition is actually the definition of $\lambda$ as the marginal utility of income:

$$
\frac{\partial u}{\partial x_i} = \lambda p_i + \kappa_i a_i
$$  \[2.16\]

$$
\frac{\partial u}{\partial t_i} = \mu - \kappa_i
$$  \[2.17\]

The marginal rate of substitution between the time spent on commodity $T_i$ and the good $i$ at the maximum level of utility, we divide the second first order condition by the third, and obtain:

$$
\frac{\partial u}{\partial y} = \lambda
$$  \[2.18\]

and the last condition concerning the effect of technical minimum time required:

$$
\kappa_i(T_i - a_i x_i) = 0
$$  \[2.19\]

This is referred to as value of time as a commodity in activity $i$. The difference between $\frac{\mu}{\lambda}$ and $\frac{u - \kappa_i}{\lambda}$ is binding if $\kappa_i \neq 0$, which is the valid case in most travel situations. This difference is the value of time-saving in activity $i$.

If an individual is free to choose the time spend on $i$, then she will only spend the amount $T$ in such a way that at the margin its value is equal to its shadow price $\frac{\mu}{\lambda}$. The shadow price is the marginal price of time as a resource, if it is homogenous and its value is same in all activities and the maximum utility can be obtained from this activity. However, one is constrained to spend at least the amount of $a_i x_i$ and assuming this level exceeds the level at which the individual derives the optimal value from time consumption, then the marginal rate obtained from time is less than its shadow price. The difference is the loss of utility of time spent in this activity. As stated before, this is the value of time-saving. (DeSerpa, 1971; Hensher and Brewer, 2001). With this theoretical framework, a lot of research has been done to quantify the value of travel time savings.

Winston (1982) elaborated further on Becker’s and DeSerpa’s work by restating the model in a continuous time form, adding switching cost and benefits of synchronisation (implying the inclusion of consumption and scheduling functions of others). He also introduced the difference between ‘goal utility’ and ‘process utility’. For most types of travel may be assumed that the goal utility is positive and often even high, whereas the process utility (how enjoyable the pastime is while travelling) is often low or even negative (when compared to many alternative time uses).

The nasty effect of travel in adverse weather is that the effort has to go up, implying that costs go up, whereas the process utility gets even lower (i.e. the value of alternative time use goes up) and the goal utility remains the same. If the effects of the anticipated extra cost and lowered process utility become too high as compared to the expect goal utility, a consumer will reconsider the trip.
Depending on the available (weather) information it could cancel, postpone or reorient the trip (new destination).

After the above explanations it may come less as a surprise that travel demand modelling is carried out in various layers, in which subsequently trip generation, mode choice, departure time, route choice are handled. As a consequence these are often mixed models, including both discrete choice and conditional demand models (see next section and references.)

2.3.2. Econometric models of travel demand

It is possible to develop an aggregate travel demand model based on a realistic representation of travel decision making at the micro level (agent based modelling). Aggregate models provide important insights into the working of the transport system as a whole. Aggregate demand is the result of aggregation over the population of individuals. They are assumed to act with the above utility-maximisation setting. However, the individual decisions with respect to choices are complex. In addition, these choices need to be analysed in the context of e.g. demographic characteristics and simultaneous choices such as automobile ownership or housing location. (McFadden, 1974).

The aggregate results of these choices can be estimated with a various statistical tools. The simplest form is the linear regression model where the dependent variable is continuous (e.g. number of trips) and which aims to reveal the taste weights to be attached to each attribute that is explaining the variation of the travel issue to be studied – such as number of trips. An example of a model we could try to estimate is of the following form:

\[ Q = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n(x_n) + \epsilon, \tag{2.21} \]

where \( Q \) could be the number of trips, \( x_1, \ldots, x_n \) attributes (such as the income, car ownership or some kind of weather index) and \( \beta_0, \ldots, \beta_n \) different taste weights for these attributes. Applying the OLS (Ordinary least squares) procedure, we get the estimates \( b_0, \ldots, b_n \) for these taste weights. (For example one might assume that income and car ownership have positive taste weights if \( Q \) is the number of trip made with car). OLS is a very standard method to study regression and thus not further explained here. These models can be refined by estimating for subsets, e.g. trips of car owners only or home-work trips only or urban trips only, etc.

Transport decisions often involve making choices between alternative ways of travelling (mode selection, timing, destination etc.). These limited alternatives are referred to as a set of mutually exclusive discrete alternatives. To explain the choices, we seek for an explanation why a particular alternative was chosen. The procedure to tackle this question is called discrete choice modelling. The distribution of demand in a population is the result of the individual utility maximization. Utilities are treated as random variables. This is not to reflect a lack of rationality by the decision-makers, but to reflect to the lack of information (of the researcher) of relevant but unknown factors.

The random utility model of discrete choice

This model requires four primary ingredients (Polak and Heertje, 1993):
1. a population \( I \) of decision makers \( i \) which
2. objects of travel choice (such as routes, modes, destinations etc.) and a set \( A \) of travel options available to \( i \)
3. decision-relevant characteristics \( z \) of both the decision maker \( i \) and the alternative \( a \)
4. a decision rule to combine them

The hypothesis of utility maximization plays a key role in the model. It is assumed that there is a utility function \( U \), and a decision maker \( i \) who prefers option \( a \) to \( a_1 \) when:

\[
U(x_{ia}) > U(x_{ia_1}), \text{ for all } a, a_1 \in A
\]  

[2.22]

Not all attributes characterizing the decision makers and alternatives which are relevant to choices are known to the researcher, thus it is not possible to measure all the values of the relevant attributes. There might also be unobserved variation in the population \( I \). These inherent uncertainties are dealt with using random utility functions:

\[
U_{ia} = U[f_1(x_{ia}), f_2(x_{ia}), f_3(\varepsilon_{ia})]
\]  

[2.23]

where \( U_{ia} \) is the overall utility of alternative \( a \), \( f_1(x_{ia}) \) is the function measuring the systematic taste of decision-makers, \( f_2(x_{ia}) \) is a random function representing the idiosyncratic variations in taste between the decision-makers and, \( f_3(\varepsilon_{ia}) \) is the random disturbance term, \( x_{ia} \) represents the observed characteristics of both the decision \( a \) and the decision-maker \( i \). The utility value for alternative \( a \) may then be expressed as:

\[
U_{ia} = x_{ia} \beta + (x_{ia} \delta_{i} + \zeta_{ia}) = v_{ia} + \varepsilon_{ia},
\]  

[2.24]

where the first term on the right hand side is the systematic component of utility and the second term denotes the random component. (Polak and Heertje, 1993). From these equations we get that alternative \( i \) is chosen if,

\[
(v_{ia} + \varepsilon_{ia}) > (v_{ia_1} + \varepsilon_{ia_1}),
\]  

[2.25]

but the difference \( (\varepsilon_{ia} - \varepsilon_{ia_1}) \) is unobservable. Only statements about the probability of a choice outcome can be made. The probability that the difference \( (\varepsilon_{ia} - \varepsilon_{ia_1}) \) will be less than the difference \( (v_{ia} - v_{ia_1}) \) needs to be calculated. This leads to the following equation (Hensher and Brewer, 2001):

\[
P_{ia} = P[\{\epsilon(x_{ia}) - \epsilon(x_{a})\} < \{V(x_{ia}) - V(x_{ia_1})\}], \text{ for all } a \neq a_1
\]  

[2.26]

This is the probability that a randomly drawn individual \( i \) from population \( I \), who is described by attributes \( x \) and choice set \( A \), will choose \( a \), equals the probability that the difference between the random utility of alternatives \( a_1 \) and \( a \) is less than the difference between the systematic utility levels of alternatives \( a \) and \( a_1 \) for all alternatives in the choice set. To be able to apply statistical analysis, we need to make assumptions how \( \epsilon(x_{ia}) \) is distributed in the sample population and across different alternatives in the choice set \( A \). (Hensher and Brewer, 2001). An assumption that is most widely used is called independently and identically distributed (IID) unobserved influences.
After these assumptions, we can calculate the probability that an individual would rank alternative \( a \) higher than any other alternative in the choice set \( A \), conditional on knowing \( V_{ia} \) for all \( n \) alternatives in the choice set \( A \). Once an assumption is made about the joint distribution of the random disturbance terms (usually IID) and the \( V_{ia} \)'s are specified, maximum likelihood estimation is applied to estimate the empirical magnitude of the taste weights. One basic choice model that is consistent with the assumptions is called the multinomial logit model: (Hensher and Brewer, 2001).

\[
P_{ia} = \frac{\exp V_{ia}}{\sum_{a=1}^{n} \exp V_{ia}}
\]

[2.27]

This is an example of logit regression model which are used for discrete variables (as an opposite to the OLS that deals with continuous variables). The most widely used generalization of the MNL form is the nested multinomial logit model. An illustration of NMNL model is in figure 2.4. In MNL model one would treat different modes as distinctly independent alternatives whereas in NMNL model the trip decision process is of the recursive sequential choice structure. Results of the decisions on the lower level feed info to the higher level. (Polak and Heertje, 1993).

**Figure 2.4** Alternative decision structures of MNL and NMNL for a mode choice

2.3.3. Substitutes

If the good or service \( x \) has an imperfect or perfect substitute and something causes the demand for good \( x \) to decrease, some or all of the decreased demand flows to the demand of the substitute. We can call this other good \( x_2 \). Thus, if the demand for good \( x_2 \) goes up when the price of good \( x \) goes up, then we say that good \( x_2 \) is a substitute for good \( x \). To put it more formally, good \( x_2 \) is a substitute for good \( x \) if

\[
\frac{\Delta x_2}{\Delta p_x} > 0.
\]
The effect is shown in figure 2.5. The blue arrow represents the movement of the demand curve of good $x_2$. This movement is partly explained by the substitution effect. As the price of $x$ has gone up, the relative price of $x_2$ has gone down and people consume more of good $x_2$. If the preferences have changed and the utility of consuming good $x$ has gone down, the demand curve of the substitute $x_2$ will shift onward to the right. There is also another effect that will cause a reverse effect on the demand curve of good $x_2$ shifting it back to the left. When the price of good $x$ becomes more expensive it means that the available income will buy less of good $x$. The purchasing power of income has gone down and it will shift the demand curves to the left. The more close substitutes good $x$ has the smaller the income effect turns out to be as more of good $x$ is dropped out of the consumption bundle. (Varian 1999, 147).

**Figure 2.5 Changes in the demand of a substitute**

As long as consumers' have substitutes, the utility lost for consuming a specific good at a lower than the original level – say because of an extreme weather event – is not as large as it would be otherwise. This is also an important fact regarding the mitigation costs against adverse weather. We cannot simply think that the cost of mitigation is the loss of utility for not being able to do something – for example cancel a road trip to grandmother – but the differential of utility gained from the road trip by a car compared to taking it by a train.

### 2.4. Market equilibriums

At the equilibrium supply and demand are equal and determine the market price $P_0$ and quantity $Q_0$. All other factors are given, including the state of weather $W_0$. Figure 2.6 shows the initial equilibrium in a competitive market.
Figure 2.6 Original equilibrium of particular sector

The producer surplus is defined as the balance of total revenue ($p_0 Q_0$) and the costs of producing the quantity – i.e. in figure 2.6 the area under the supply curve up to $Q$. The consumer surplus is the balance what a consumer would be willing to pay for a product (utility from a product) and the price they actually pay. Both of the surpluses are shown in figure 2.6.

What happens if an exogenous shock, such as an extreme weather event, enters the model and how does it affect consumer and producer surpluses? It depends whether adverse weather affects the demand, the supply or both; it depends how sensitive demand and supply are related to specific weather events (how much the curve shifts); it depends on the price elasticities of supply and demand (how steep are the slopes of the curves) and a number of other factors e.g. different sectors and modes which are substitutes or complements to the given sector. An example of the shift in the equilibrium is however provided. Figure 2.7 depicts a situation where an adverse weather event has an effect on both supply and demand. Under extreme weather conditions a new equilibrium is reached. At this new equilibrium the gross benefits of the sector will go down. If the shifts are equal, the price level does not change. In this example, supply is reduced more than the demand and the price level goes up from $p_0$ to $p_1$. The quantity exchanged drops from $Q_0$ to $Q_1$. 

Figure 2.6 Original equilibrium of particular sector

![Diagram of original equilibrium](image-url)
In the original equilibrium the sum of consumer and producer surpluses – *social surplus* - was the triangle between the blue demand curve $D_0$ and supply curve $S_0$. During the extreme weather however both producer and consumer surpluses go down. The total welfare loss of the sector from an adverse effect is the sum of lost producer and consumer surpluses. Whenever the demand or supply curves shift in any direction the welfare obtained from the particular sector is changed. This change in the welfare is the appropriate measure for the economic value of the change. The amount of changed social surplus is also what we try to find out when we are estimating the value of weather information. How much the supply and demand curves shift because of weather information and how much it affects the social surplus. (Varian 1999).

However, the overall effect of the extreme weather event depends also on the reaction of other sectors.

When an extreme weather event hits a sector, people spend less money on the services from the sector in question and change their consumption to alternative sectors. Demand of perfect or imperfect substitutes will increase if the adverse weather does not have a direct effect on these goods or services. Some of the reduced social surplus is then gained back from other sectors as people reallocate their consumption. This effect is shown in figure 2.8.
2.5. Transport markets

In economics, the market is an abstract concept providing the interface between supply and demand for a particular good. This interface determines the price of exchange and the quantities exchanged. In transport we have to relax some of the assumptions of competitive and fast-reacting markets. Examples are numerous: some of the supply of transportation lies entirely outside of the markets and is rather determined by the nature or by the government, whereas the demand for a good and the quantity exchanged can be determined prior to the knowledge of the actual price. (Polak and Heertje 1993).

The demand and supply still follow the same economic theory provided in the earlier chapters, but some of the assumptions of pure, instantaneous, competitive markets must be relaxed. Instead of one market we usually have to focus on a multiple markets at the same time, to estimate the effects of a policy change, price increase – or an occurrence of an extreme weather event. This is because markets are interlinked on the demand side by the possibility of mode substitution and on the supply side by suppliers who compete for the same inputs or customers. Competition is often restricted by natural barriers such as economies of scale and density (diminishing marginal costs of production) or by artificial barriers such as government intervention. The maximum capacity of a transport mode is usually fixed on a short-term because increasing capacity would require long-term investments. (Hensher and Brewer 2001).

Extreme weather events have effects on transportation in every sector and mode. The direct and indirect impacts vary between sectors and modes. A snow storm, for example, reduces road friction and visibility which causes temporary degradation of the transport system. As the transport system becomes unreliable or even dangerous, people change their normal or otherwise

Figure 2.8 Changed equilibrium in the market of a substitute
preferred travel choices. Usually consumers have to pay a bigger price for the transportation as they are exposed to delays, increased ticket prices or increased fuel consumption.

In the short-run, an individual’s travel choices consist of pre-trip decisions (destination, mode, route and departure time choices) and en-route decisions (alternative route or stoppage) (Polak and Heertje, 1993). Because en-route decisions are very limited, the decision which transport mode to use is usually done prior the actual trip. Thus, in the short-run, demand elasticities (both direct price and cross-elasticity) are typically very low and demand is relatively inelastic (Button 1993; Hensher and Brewer 2001). In the long-run people can alter their employment or residential location, housing type or automobile ownership. In the short-run however, the change in the price level has usually a very small effect on the consumption of the particular good and on the consumption of potential substitutes. The most price insensitive demand is experienced during the week on the peak-times. With better weather forecasts however (more accurate, longer lead times) consumers of various transport modes would be aware earlier of the en-route conditions and could make better pre-trip decisions. Better decisions include switch from one mode to another, earlier departure, choosing a different destination or a safer route. Chapter 3 explains how these decisions are made based on weather forecasts or rather weather information service. Qualitative benefits of weather forecast are listed on the chapter 4 for each transport mode as well as some estimates of the quantitative values.

Next we show an example of two transport modes: road transport and rail transport to illustrate some important concepts of transport economics. How different weather events actually affect the quantity or volume of the traffic is an empirical question and depends on the weather phenomena, transport mode, day of the week and many other factors. Some of the weather effects affect the supply side of a given sector (reduced capacity, higher total costs) and some affect the demand side (higher price and less utility gained from the consumption of a given transportation mode). Chapter 4 gives a more detailed review on these matters for each transportation sector and what kind of benefits could weather forecasts provide e.g. in forecasting demand and avoiding accidents. Following example is only presented here to show some of the possible consequences of an extreme weather event and the mechanisms of the transport markets.

2.5.1. An example of consequences of an extreme weather event, mode substitution and weather information

The considered example is depicted in the figure 2.9. Road transportation is normally at level $Q_0$ with a price of $p_0$. The potential road capacity is fixed in the short-run and demand is balanced with the road capacity. When an extreme weather event hits the road transportation system, road conditions get worse and the road system can support a lesser number of trips for a given time period. This results the road capacity or supply curve to shift left to $Q_1$. Without prior knowledge of the weather conditions the demand curve stays on its original level at $D_0$, but the price of driving is increased by the reduced capacity which leads to time costs. Without weather information, the only travel plan modifications possible are en-route and just-before-trip modifications. Demand for road transportation is highly inelastic to the price level and the demand curve is very steep. With weather forecasts however, drivers are aware of the increased price level already before the trip and are able to make pre-trip modifications to travel plans. Some of the cautious road transportation users might even make an exception to their normal routine and use public
transportation. The demand curve $D_i$ has shifted to the left and is more sensitive to price variations. Also the supply side reacts to the weather information. It is shown in chapter 4 how weather forecasts help the road maintenance companies to allocate their resources more efficiently. Better route choices made by people also improve the road capacity. The new road capacity is denoted by $Q_i$ in the picture. As a result of the weather information, the new price level is lower and more cars are able to get in destination in a specific time; the transportation market is less upset.

Figure 2.9 Extreme weather event hits road transportation on peak-time

Other transportation modes are indirectly influenced by the extreme weather event too. Figure 2.10 shows an example of modal substitution. It shows how the changes in road transportation due to bad weather and weather forecasts could have an effect on rail transport. It is assumed that rail transport itself is neutral to the weather extreme.

As the price of driving goes up, the demand for train services goes up and demand curve shifts to $D_1$ (substitution effect). Train companies might be able to increase capacity on a short notice by adding more train cars to peak-time trains for example. This is why the supply curves are not completely vertical like in road transportation. The price of train trips goes up from $p_0$ to $p_1$, because infrequent travelers usually pay more for their tickets than everyday passengers (with season cards etc.) and because of some delays. The number of trips goes up from $Q_0$ to $Q_1$.

With the weather forecasts however the substitute effect is even higher in the occasion of extreme weather events. Travellers preferring road transportation are able to make better pre-trip judgments, and use trains rather than cars during these events. Demand curve shifts to from $D_1$ to $D_i$. The capacity of rails might be increased to meet the increased demand. With weather forecasts and longer lead-times rail road companies are able to reserve more passenger cars, plan working hours of employees and maybe run some extra trains outside the usual schedules.
The supply curve could shift from $S_1$ to $S_2$. As a result, more infrequent travellers are aboard ($Q_1$ to $Q_2$) and a higher price ($p_1$ to $p_2$) is paid for the train tickets on average.

Figure 2.10  Rail transport as a modal substitute
3. The quality and value of weather information

Weather data, observation and forecasts are public goods in most countries. It means that weather information is produced with tax money collected from the citizens, and the data is made freely available or at a highly subsidized user cost. As weather information is a public good there is no market for it to determine the equilibrium price under the forces of supply and demand. There is thus little or no market data at all for weather information (Lazo and Chestnut 2002). The benefits of such a public system are hard to calculate yet the calculation – or at least estimation - is needed for the economic rationalization for the production of weather information. Benefits need to be greater than the costs to justify the public system. Here we try to evaluate the benefits of weather forecasts on transportation. The evaluation is mostly based on literature review and simple case studies and is not meant to be exhaustive at any level.

3.1. *Developments in weather forecast quality*

Evaluation of weather forecast quality, commonly referred to as forecast verification is a highly important and integral component in all weather related research as well as operational weather service activities and applications. To be able to perform any credible verification efforts one must always first define and design the scope, goals and applicable verification methods and measures properly. Moreover, the user(s) of verification outcome need to be distinguished. Verification results will only then be useful in providing plausible answers to different questions addressed by various target groups like meteorological scientists, weather forecasters and end-users of forecast information. Regarding the transport sector, different transport modes have most probably different questions that need to be tackled. Verification can hence be considered as an efficient tool to direct research activities, to help forecasting centres in monitoring whether their forecasting capabilities are improving with time (i.e. trend analysis), or to support decision-making procedures relating to weather dependent actions.

Meteorological verification typically involves the computation of a comprehensive set of dedicated verification measures and statistics over huge datasets of meteorological forecast-observation pairs. The observations are most typically upper-air or surface point observations of meteorological variables, or these observations formed into two-dimensional grid analyses covering defined geographical areas of interest. The most common verification methods provide overall assessments on the general quality and skill of the forecasts. They do not necessarily provide actual diagnostic information of the quality. Suffice to say that forecast verification is a wide field of science of its own and will not be touched in any detail in this context.

Probably the most important area in weather forecast quality assessment is the verification of extreme, high-impact adverse weather events, very much because of the increase in recurrence and amplitude of such events. On the other hand, rare event verification is notoriously difficult due to the scarcity of events and leading to large sampling uncertainties in the eventual aggregated verification statistics.
This chapter provides a brief insight into historical developments and trends in weather forecast quality during the past few decades, as well as providing a very rough estimation of the expectations for the future. As mentioned above, it is of utmost importance for a weather service to keep abreast of the performance of its service products. The Finnish Meteorological Institute has for long been the international forerunner in verification expertise and activities, and a forecast verification system has been running operationally since the early 1980s. The aggregated datasets enable long-term trend analysis of the Institute’s operational forecast quality. Just as an example, the verification results confirm a remarkable improvement in “human-made” surface temperature forecasts: today’s two-day forecasts are better than the one-day forecasts of the mid-1980s (Nurmi and Brockmann 2007).

The results referred to above represent forecast quality improvements by operational duty meteorologists. We can also look at the potential quality improvements in the performance of the numerical weather prediction models, which are being effectively used by duty meteorologists as their forecasting guidance in their everyday work. Figures 3.1 and 3.2 represent such results for forecast performance in the upper parts of the atmosphere, at the height of c. 5 km above ground (Fig. 3.1) and for surface weather, namely the precipitation (Fig. 3.2). The upper atmosphere is a highly relevant reference, because it is there the meteorologist focuses when formulating the view of the expected general circulation and large-scale weather patterns. It is also easier to produce forecasts of general atmospheric features than of the surface weather. One can see from Figure 3.1 that the predictability or, in other words the usefulness, in number of days, of the forecasts of the free atmosphere circulation patterns was about four (4) days in the early 1990s, circa five (5) days in the year 2000, and today six (6) days. The respective results for the predictability of model produced precipitation were two (2) days in the mid-1990s and today about 3.5 days (Fig. 3.2).

**Figure 3.1** Evolution of the predictability in the free atmosphere (500 hPa geopotential height), 1990-2010, by the ECMWF numerical weather prediction model (after © ECMWF).
From these results it is obvious that (i) there are differences in the forecasting capability of different weather variables, (ii) there is a definite positive trend in the forecasting capability of all the weather variables, and (iii) the improvement in forecast quality has a more or a less steady increase of one day per decade. It is, therefore, realistic to believe that a similar trend will continue and that the predictability of the atmospheric variables and, consequently, the usefulness of final weather forecasts will evolve by one day per decade until the foreseeable future. Such explicit results can be utilized in supporting the weather critical decision-making and the value assessments in weather services. As an example of the practical application of such quality assessment information, Finnish Meteorological Institute has set as one of its official 5-year performance targets (for the year 2015) that the precipitation forecasts should be useful at least up to 104 hour forecast range, i.e. for more than four days.

3.2. Value of information in individual decision-making

In theory, weather information can simply be viewed as a factor in the decision process that can be used to maximize the value or utility of the decision in hand. Theory is explained in great detail for example in Katz and Murphy (1997). The point is that the value of weather information is the difference of utility from a decision with a weather forecast compared to a decision with only prior climatological information. So the value can be expressed with the following equation:

\[ Value = E_i(u[c(ai, \ldots)]) - E(u[c(a0, \ldots)]) \]  

[3.1]

where: \( ai \) and \( a0 \) are optimal set of choices with and without information respectively, \( c \)=consequences dependent on the actions, \( u \)=utility dependent first on the consequences and second from the actions.
There are a couple of background assumptions that merit mentioning. First, only in theory people are able to maximize their utility with a mathematic precision. The above value denotes the maximum amount that a decision maker should be willing to pay for the weather information. For example, on the basis of economic time use theory (section 2.3) habit formation can be explained. The implication of habits is that either (new) information need or new information supply need to surpass threshold values to incite reconsideration of (routine) decisions by a consumer. Second, it is assumed that individuals have prior beliefs about the distribution of weather conditions and outcomes resulting from the conditions. Individual’s behaviour with respect to future weather conditions is therefore often modelled as decision making under risk rather than uncertainty (Lazo and Chestnut 2002), as first defined by Knight (1921). Most probably people have some kind of notion of their confidence in weather forecasts, but in terms of its rating that notion of confidence could be rather fuzzy. Third, above illustration of value is ex post in nature in the sense that information is valued after the forecast has been received (Katz and Murphy 1997). In other words in fact a learning cycle is assumed. Finally, in many examples of this model decision-makers are assumed to be risk-neutral. However risk attitudes can play an important role in the valuation of information.

3.2.1. Use of weather information

Usually the examples of the use of weather information include a simple structure: whether the decision maker should take or not to take some specific protective action against a specific unfavourable weather condition. Examples of such illustrations can be found e.g. in Katz and Murphy (1997), Nelson and Winter (1964) or Thornes (2001). All of the mentioned examples share the same pattern: taking the protective action involves a certain cost while not taking the action results in a greater loss if unfavourable weather condition occurs. This holds true in most everyday situations that decision makers are facing and is a good illustration of the problem. Therefor one example of such calculation is presented here. This Cost-loss model can also be presented in a form of expense matrix shown in table 3.1, where C denotes cost and L loss for the individual.

<table>
<thead>
<tr>
<th>Action</th>
<th>Adverse weather</th>
<th>Not adverse weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>No protection</td>
<td>L</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.1 expense matrix for the Cost-loss model

The following example is from Katz and Murphy (1997). The pattern is anyhow the same in all of the examples mentioned above, only the numbers vary:

In this example C=0.25 and L=1. When the protective measure is taken a decision maker faces a cost of 0.25. If the climatological probability for adverse weather is 0.3, the expected expense when the protective action is not taken is 0.3 and the protective action should be taken (0.3>0.25). Of course, if the probability for adverse weather based on climatological probabilities is 0.2, the protective measure should not be taken (0.2<0.25).

As it was shown p=0.2 is too low probability for an adverse weather phenomena for the decision-maker to take protective action. Next, let’s suppose that decision maker has weather information available. Quality of the weather forecast is defined with the following equation:

38/92
\[ q = \frac{p_1 - p}{1 - p} \]  

where \( q \) denotes the forecast quality (and \( 0 < q < p_1 \)), \( p_1 \) is the conditional probability of adverse weather (given that adverse weather was forecast), \( p \) is the climatologic probability of adverse weather and \( p_0 \) is the conditional probability of adverse weather given that good weather was forecast.

\[ p_0 = \frac{(1-p_1)p}{1-p} . \]

The forecast quality varies within the interval \([0;1]\). If \( q = 0 \), it equals climatologic information, while if \( q = 1 \) it is a perfect forecast system. We assume that the forecasts of adverse weather are issued with the same long-run frequency as the adverse weather actually occurs. The probability that an adverse weather forecast is issued \((Z=1)\) is then 0.2 and the probability that good weather \((Z=0)\) is forecast is 0.8. Basically this means that - on average - every fifth day an adverse weather phenomenon is experienced and every fifth day an adverse weather forecast is issued. The match of the experienced weather and the forecast weather is denoted with the quality parameter \( q \).

In this example the quality of weather information is \( q=0.1 \). The low value of quality parameter \( q \) means that the forecasts and the weather phenomena have only a low statistical match. The conditional probabilities are \( p_1 = 0.28 \) and \( p_0 = 0.18 \). Decision-maker receives a forecast \( Z=1 \). If protective action is taken, the expected cost is 0.25 and if not, expected cost is \( 0.28 \times 1 = 0.28 \), so the protective action is chosen. If a forecast of good weather is issued, the expected cost is 0.18 without protective action, which rates lower than the expected cost of protection (0.25). As a consequence the decision maker chooses not to take protective action. Value of the weather information is then the difference in the expected costs between the decisions with and without weather information.

In this case the value is \((0.2 \times 1) - (0.2 \times 0.25 + 0.8 \times 0.18) = 0.006\)

In other words the value added of systematically using the weather forecast is the difference between the climatic probability times the incurred damage without protection and the sum of the occurrence frequency of adverse weather times the protection and the occurrence frequency of good weather times expected value of incurred damage without protection (when occurring against the odds).

If the uncertainty range around the forecast probability is significant and/or prevention cost 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 the complicated version the effect of 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. If the decision maker represents a monopolistic transport company there are no regret cost of deciding differently than the others, but if there are competitors it may be that rewards get very high for the company that dares to continue services despite a forecast for adverse weather (and conversely penalties higher if others continue services against the odds). Similarly, if standard deviations of
the accuracy of consecutive adverse weather forecasts are rather large, decision makers may wish to account for that as well, especially in competitive markets.

**The value of better information in case of improved accuracy**

Another example (Katz and Murphy 1997) demonstrates how higher quality of weather forecasts increases the value of weather information. In this example everything else is equal but quality of the forecast system is \( q = 0.5 \) and corresponding conditional probabilities are \( p_1 = 0.6, p_0 = 0.1 \). In this case protective action is taken when \( Z = 1 \) (0.6 > 0.25) and not taken when \( Z = 0 \) (0.1 < 0.25). Expected value of weather information is then \( 0.2 - (0.2 \times 0.25 + 0.8 \times 0.1) = 0.07 \). With similar calculations we get zero value for weather information of \( q = 0.05 \) and a value of 0.15 for a perfect forecast system (protective action is taken always/only when needed). As the quality (=accuracy) of the weather information system improves so does the value of the system for the decision-maker but only after a certain threshold where the value is zero. General result can be expressed by the following equation:

\[
V(q) = p[(p + (1 - p)q)L - C, q^* \leq q \leq 1]
\]

Where \( q^* \) is the lowest quality of weather forecast system with value, calculated as follows:

\[
q^* = \frac{C}{L - p}
\]

The method presented above 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 (see section 3.3).

### 3.2.2. Factors that determine the value of information

Accuracy of the forecast is not the only factor that determines the value of the weather information. Some of the other value determining factors were already present in the previous example but here they are presented more formally. List of relevant factors is from a paper “benefits and costs of early warning systems for major natural hazards” (Teisberg and Weiher, 2009) but it is applicable for this study also, albeit with some modifications:

1) Frequency – is the adverse weather common or rare, or as in the previous example: what is the climatological probability of the weather event

2) Severity – what is the magnitude of the risk to life or the damage to property that the hazard could cause? In the previous example adverse weather caused the same loss always when it occurred, in real world the loss is more random.
3) Lead-time – the time between the forecast and the occurrence of the event - determines the range of protective action that the decision maker has available, longer lead times means wider range of possible responses and therefor usually smaller response costs.

4) Accuracy – as described before, accuracy determines whether one should make costly changes in behaviour to protect oneself from possibly adverse consequences.

5) Response costs – what are the costs of possible responses to the warning – as described before, protective action has always a cost, for example longer travel time.

6) Loss reduction – how much are the expected losses from an adverse weather reduced given the protective actions – in the example before, by using protective measures decision maker was able to mitigate the whole loss.

In reality often only a part of the cost can be avoided. Reasons for these limitations are rooted in incomplete information, limited capabilities to interpret information, trans-action 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 weather information generation to the actual response. The weather service value chain assessment approach is presented in the next section.

In relation to forecast skill indicator development several authors have already hinted at the need for elaborating on 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 in more sophisticated ways with the effects of uncertainty and confidence on the use of weather information (Wilks 2001). A second line deals with variations in the appreciation and uptake capability of the weather information by the user (Patt et al 2005; Sharma and Patt 2012). Combinations of the two approaches are truly scarce (an example is Millner 2008), 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 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 practical meaning in 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 forecast to realized benefit and not just for weather forecasts as such.

### 3.3. **Linking micro and macro approaches**

In the examples provided in sections 3.1.1 and 3.1.2 the focus was on the technical improvement of the weather forecast. The example 3.1.2 is a good illustration of how better forecast accuracy can create value. However, it does not do it automatically. Therefore it is necessary to understand the complete process of translating changes in forecast accuracy into values for the end-users. Hooke and Pielke (2000) present a simple model of this process and identify three steps of the weather forecast system:

\[
\text{predict} \rightarrow \text{communicate} \rightarrow \text{use}
\]
Perrels et al. (2012) further 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 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 (predict)
2) the extent to which weather forecast information contains appropriate data for a potential user (predict and communicate)
3) the extent to which a decision maker has (timely) access to weather forecast information (communicate)
4) the extent to which a decision maker adequately understands weather forecast information (communicate)
5) the extent to which a decision maker can use weather forecast information to effectively adapt behaviour (use)
6) the extent to which recommended responses actually help to avoid damage due to unfavourable weather information (use)
7) the extent to which benefits from adapted action or decision are transferred to other economic agents (use)

The more professional and meteorologically skilled the end-user is the lesser the filters affect the attainable value added generated by the use of weather services. Therefore better accuracy and lead-time of weather forecasts might create value just from these improvements of the prediction part. As regards transportation these users might include decision-makers in aviation and marine navigation industries. On the other hand for some road users (non-professional traffic modes) the significance and improvement potential of these steps will weigh more. Therefore, they are studied in greater detail depending on the traffic mode later in this study.

The above 7 stage list can be used both in a managerial indicative fashion (e.g. by adding options for improvement, see chapter 4) as well as in a quantitative analytical framework. In chapter 6 a quantitative application will be presented, whereas here only the methodology will be explained.

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:

\[
Q_{mt} = \Pi_{s=1}^{7} \{ P_{ms} \}
\]  

[3.6]

where \( 0 \leq P_{ms} = f_{ms}(x_{s_1}, ..., x_{s_{1+n}}) \leq 1 \), and therefore also \( 0 \leq Q_{mt} \leq 1 \)
The realized benefit for mode \( m \) in year \( t \) (\( B_{mt} \)) is the product of the fraction \( Q \) and the hypothetical maximum benefit score, corrected for possible non-linearity effects between the achieved fraction \( Q \) and realized benefit \( B_{mt} \):

\[
B_{mt} = Q_{mt} \cdot y^{a(1-Q_{mt})} B_{mt}^\text{max}
\]  

The establishment of the hypothetical maximum score \( B_{mt}^\text{max} \) 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. \( \Delta Q \) 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:

\[
P_{ms} = \left[ \sum_{j=1}^{M} \sum_{i=1}^{N} P_{j,i} \right]_{M,N}
\]

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:

\[
p_{j,i} = \frac{e^z}{1+e^z}
\]

where \( z \) is explained by one or several background variables

\[
z = \beta_0 + \sum_{i=1}^{n} \beta_i x_i
\]

\( x_i \) 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 \( x_i \).
3.4. **Different valuation approaches**

3.4.1. **Prescriptive and descriptive**

There is a distinction between the prescriptive and descriptive approaches and studies in evaluating the value of weather information. Prescriptive model assume that decision makers are able to use all the information, make rational choices and maximize their expected utilities. On the other hand, descriptive models try to model the decisions and actual behaviour in a decision-making process. Discrepancies between the two approaches are inevitable because people do not necessarily follow prescriptive decision-making models. (Hooke and Pielke 2000).

The challenge of providing better weather information for individuals cannot thus be solved simply by providing more and more forecasts on a more frequent basis. If decision makers have already difficulty using existing products, the difficulties will not vanish by providing more information. How weather information is actually used can be modelled by the weather service value chain (Perrels et al. 2011); the uptake and the use of weather services is subject to several filters when considering the entire chain from weather information to end-users response.

Because people tend to make decisions that are not entirely rational and because of misinterpretations of weather forecasts, descriptive models must account also users’ interpretations of forecasts. Lazo and Chestnut (2002) also noted that it is not possible to develop a single descriptive or prescriptive model that represents all users of the weather data. Only in a few occasions the decision maker has documented an explicit model for the use of weather data – like in aviation industry in case of some specific events. However, estimating the value of weather forecast for aviation would be like estimating the value of air for people - without weather observations and forecasts airplanes would not fly. Estimating the value of better forecast accuracy might be possible if the necessary data about distributions of weather events and costs were obtained.

Prescriptive studies evaluate the amount of money that users would be willing to pay for the information – “the best price for the current weather information”. Descriptive studies try to evaluate the realistic value of weather information for the end-users. They are both based on the calculation of the expected utility with and without weather information. Some more straightforward non-market valuation methods have also been implemented in research.

3.4.2. **User surveys**

One approach of studying the economic value of forecasts is to complete a survey on experts or users of the weather information. Surveys can be divided in three main categories depending on the questions asked. Two of them are descriptive on their nature; third is an alternative non-market valuation method:

1) Revealed preference – How did an expert or user react to some relevant information in his decision-making process
2) Stated preference – How would an expert or user react to some relevant information in his decision-making process

3) Willingness-to-pay and Willingness-to-accept – In contrast to stated preference, willingness-to-pay is a stated value (SV) experiment, where experts of users are asked how much they would be willing to pay for a lower, current or improved level of service. Willingness-to-accept means asking users how much money would they need to get for giving up for something they already have – like the weather information system.

Contingent valuation (CV) is a demand based method to determine values for non-market goods and services. CV relies on hypothetical market-like scenarios to provide data that are used to estimate benefits (Rollins & Shaykewich 2003). One of the contingent valuation methods is called stated value method. In this method data is collected by surveys that try to estimate the maximum amounts people would be willing to pay (WTP) to receive or would be willing to accept (WTA) to forgo a specific level or quality of a service. Rather than modelling the production process, as given in the simplified example in 2.1.1, demand-based methods assume that the users of the service know the maximum amount that they would be willing to pay for a service or the improvement of the current service. While cost-avoidance methods might work in case of a particular production process, demand-based methods are applicable in estimating broader benefits. (Rollins and Shaykewich 2003).

Some economist are sceptical about contingent valuation methods which are based on user surveys and think that they are unable to derive realistic estimates of forecast value because they do not reveal how forecasts are used (Katz and Murphy 1997) while some economists suggest that respondents might be unable to make realistic quantitative estimates (Brown and Murphy 1997). Katz and Murphy (1997) pointed out that surveys might at least reveal subjective forecast value of the respondents. Lazo and Chestnut (2002) noted that from the perspective of welfare economics, which is the basis of benefit-cost analysis, individual’s subjective values are the valid measures of welfare change.

There are several important points that need to be taken into consideration when conducting a SV study. Studies need to clearly define the commodity to be valued (e.g. weather information) and respondents need to be informed about the framework of the hypothetical transaction; like inform about the marketplace of the transaction and remind respondents about their budget constraints. (Lazo and Chestnut 2002). When these conditions are met respondents are more likely to reveal their true subjective values.
4. Characteristics of forecast use and valuation in transportation

No single methodology could deal with the requirements of estimating benefits for different transportation sectors or modes. Different transportation sectors and modes need to be studied separately as they use information with very different ways and also the information used depends on the sector or a mode. The way the information is used depends how professional the operators on different sectors are. The way operators use information is described in the weather service value chain.

Also the type of weather information that is used varies between end-users. Information can be classified with two variables: indivisibility and non-exclusiveness. In general goods can be classified according to two characteristics: 1) A good is *indivisible* or non-rival if its use by one individual does not reduce its availability to others. 2) A good is *non-exclusive* if individuals cannot be excluded or it is very difficult to exclude others from using the good. Based on these concepts, the meteorological services can be divided into following sub-groups: (modified from Anaman et al. 1997)

1) non-rival and non-exclusive goods: basic public weather services, free access via different media

2) non-rival and exclusive goods: forecasts for aviation industry, these services require a fee from the end-user; the use of the service does not reduce the quality or quantity of the service from other users

3) rival goods (non-exclusive and exclusive): rival and non-exclusive goods are services dealing with recording of visually detectable weather events for which the number of weather stations recording these events has been declining. Rival and exclusive services are market goods, services are tailored to a certain end-user that pays a market price for the service

Given the nature of most meteorological services it is evident that the price or the value of a service is often not directly observed in the market. Social benefits, e.g. for road-way users, derived from the use of meteorological services are usually difficult to value in monetary terms. Tools for monetary valuation have been developed though, such as the statistical value of life. The purpose of this chapter is to give a literature review on the valuation of forecast information on different transportation sectors and modes and to describe the characteristics of information used in different sectors and how that information is used.

4.1. Aviation

Without meteorological services there couldn’t be any commercial aviation at least in its present form. Hence there is no point in calculating the value of the present weather information with a Bayesian decision theory presented in the third chapter of this study; the expected utility of a decision without weather information is impossible to evaluate in this case. The decision theory
could be useful however in evaluating the value of more accurate weather forecasts. The theoretical value would be then:

\[ E_2 (u[c(a2,\ldots)]) - E_1(u[c(a1,\ldots)]) \]

where \( a2 \) is the optimal set of choices under the new weather information and \( a1 \) optimal set of choices with the old information. This approach was used in an Australian study (Leigh 1995) where the benefits of not having to carry extra fuel were evaluated. Aviation is indeed such a risk aversive business when it comes to avoiding incidents and accidents, that better accuracy in forecasts would probably rather have a greater monetary impact on avoiding unnecessary safety costs and avoiding weather related delays than avoiding losses from accidents. This is because of the very strict rules that are concerning flying; safety comes before efficiency. The manufacturer of the plane sets the limits for the conditions in which the plane can be safely operated. The operator of the planes sets their own safety limits and the pilot’s license – based on his skill set and experience – defines the condition limits in which the pilot is allowed to fly. The strictest of these rules on each situation is used to decide whether the flight can be operated and with what safety measures.

**Effects of adverse weather**

Adverse weather affects aviation in the forms of reduced safety margins, increase in the occurrence of incidents, increase in the possibility of accidents and in the form of costs related to delays, diversions, cancellations and in-flight injuries.

One of the major expenses in the airline industry are the costs associated with flight delays. In the USA in 2005 about 25% of all delays were weather related, amounting up to billions of dollars (McCrea et al. 2007). In Finland the share of weather related delays has been even higher, about 37% between 2008-2010 (Finavia). Data about the weather related delays in Europe is collected by Eurocontrol; data is presented in chapter 6.3 of this study.

Delays are often considered to cause costs only when they occur. Airlines however avoid delay losses by adding buffer to their schedules. Hence, buffer minutes can be viewed as mitigation costs against delay losses. The number of buffer minutes is a strategic choice and a matter of compromise. Minutes of strategic buffer should be added to the point where the cost of adding those (marginal cost) equals the marginal benefits. Marginal benefits can be interpreted as the avoided marginal costs the buffer is expected to mitigate by dealing with these delays. These “hidden costs” that stem from the mitigation of delays are real costs and represent the opportunity of being able to use resources in another way by decreasing the buffers and flying more routes. (Cook et al. 2004)

Another important implication to consider is the knock-on effect in a complex network of flights. Primary delays, for reasons such as weather, have an effect also to other aircraft schedules causing reactionary delays. These delays may propagate throughout the network until the end of the same operational delay. (ibid). This is the reason why no single airport or airline can be studied in isolation. The delays that might be avoided by better forecasts have a multiple effect of benefits because not only the costs related to the primary delays are avoided but also the secondary delay costs.
A good example of secondary delays is found in Cook et al. (2004). First flight of the day from X to Y, flight $XY_1$, is 30 minutes late arriving at Y. This delay is called primary delay. Other delays caused by the primary delay are called secondary delays. For example the return flight $YX_1$ could leave 20 minutes late as a direct result of the primary delay. The network effect doesn’t stop here. The aircraft might never fully recover from the primary delay and the last flight of the day might be for example 10 minutes late. Also the primary delay might cause delays for other routes in the network too, for example to flights YP, YQ and YR – and these to routes PX, QH and so on.

**Figure 4.1 Primary delays and the network effect (Cook et. al. 2004)**

Even though it is very hard to quantify the benefits of better forecast accuracy for aviation because of the complex network of flights, some effort has been made. For example Klein et al. (2009) calculated how much delay costs could go down with better weather forecasts. They used a method called natural experiment; basically similar method is applied in this study to road accidents in chapter 6.1. Basic idea is to compare the delay costs of those days that the forecast has been accurate to those days that the weather forecast has been inaccurate.

The research process proceeds in this method as follows (modified Klein et al. 2009). 1) quantify the weather related costs and losses; 2) data from weather forecast converted in to same format as actual weather data or vice versa; 3) build a variable of the forecast error, investigate how delays are related to both type of forecast errors (either too good weather is forecast or too bad); 4) based on these finding, build a model to estimate how much delays could have been avoided with “perfect” forecast or; 5) Estimate the benefits for each step of forecast accuracy improvement. Klein et al. (2009) found an upper bound of 330 million dollars a year in the USA of avoidable costs via accurate forecasts.

As these results are for the USA only, one must remember the network effect of delays too. Additional benefits would be generated from the avoided delay costs all-around the world. Also it must be noted that these benefits are calculated on a tactical level only; in reality improved accuracy would create additional benefits on strategic-level too, when weather effects could be better incorporated into air traffic management. One example of such strategic level flight planning process is found in McCrea et al. (2007). They introduce a model that allows rerouting of flights with respect to specified probability thresholds of encountering severe weather. The model is based on a concept of probability-nets, nets representing specific weather phenomena and the size of the net representing the probability of the event. Flights and flight surrogates (available reroutes) are planned so that given a probability they try to avoid “getting caught” in the net – which would cause a delay. Limitations for this model to be used include existing inaccuracies with the current ceiling forecasts. In 2005 NOAA reported (according to McCrea 2007) that ability
to report aviation ceiling forecasts remains at 46% and improvements in the ceiling forecasts could result (only fuel savings) 250 million US dollars reductions in costs for the airline industry in a year. Similar kind of simulations to European airspace would be highly beneficial but are out of the scope of this report.

4.2. Road transport

Road transportation is divided into three groups in this study which are: 1) vehicle drivers, 2) bus and trucking operations and 3) road maintenance operations. The division is based on the factors described earlier: how each transportation mode uses the weather information and what kind of information it needs for its decision-making process.

4.2.1. Vehicle drivers

Road weather service is a traffic information service that provides road users with information on predicted road weather conditions, via the Internet and as a part of weather forecasts broadcast on television and radio (Sihvola et al. 2008). It is a part of the basic public weather services and so a non-rival and a non-exclusive good. Vehicle drivers are a very heterogeneous group and 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 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 at the vehicle drivers. A very good example of such a study is found in Lazo and Chestnut (2002) where they estimated the value of public weather services and possible improvements 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 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.

Effects of adverse weather

Adverse weather significantly affects travel decisions, mode choice and road safety. Adverse weather or extreme weather events causing different kinds of problems on road transportation have already been specified in Leviäkangas et al. (2011). They include heavy snowfall, heavy precipitation, low temperatures, wind gusts and hail.
In a case of bad weather planned trips may be postponed, deferred or cancelled. People lower their speeds to drive more safely under poor conditions which results in time losses. Also traffic safety and crash rate can increase dramatically during adverse weather. However some of these effects can be divided into losses and some into costs incurred avoiding losses, in the same sense as in the example in chapter 3.2.1. The division is important because the point of the decision making is to mitigate from the possible losses, in this case from the road accidents, so that the decision maximizes utility. Mitigation is not free and it involves costs; otherwise decision-maker would always choose to take the protective action and drive more slowly for example. Thus, it is not enough to study the avoided losses but also the costs of avoiding these losses need to be taken into account.

**Table 4.1 Expense table for a vehicle driver**

<table>
<thead>
<tr>
<th>Action</th>
<th>Adverse weather</th>
<th>Not adverse weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection</td>
<td>C=(speed reductions, cancellation, postponement, re-routing), Below &quot;highest&quot; risk of accidents, above normal</td>
<td>(cancellation, postponement, re-routing)=C-speed reductions, Below normal level of accidents</td>
</tr>
<tr>
<td>No protection</td>
<td>Highest risk of accidents</td>
<td>Normal level of accidents</td>
</tr>
</tbody>
</table>

Speed reductions need to be divided into two categories: flow speed reduction and individual speed reductions. Flow speed means the average speed of the traffic which is affected by the weather. Flow speed is something that an individual cannot control and its consequences need to be categorized as losses. Main factor which is most affected by inclement weather is flow speed. (El Faouzi, 2010). However driver can reduce speed also by his own decision to lower the risk for an accident. In this case the lost time caused by a speed reduction is a mitigation cost.

Road traffic demand decreases during adverse weather. The decrease of demand depends on the purpose of the trip (work, shopping, holiday, etc.), e.g. meaning that the drop in demand for recreational trips is much higher. Therefore the effect of adverse weather on traffic demand is much higher in weekends than during working days. It must be noted though that the decrease in demand for road transportation is partially compensated by an increase of demand for trips by other transportations modes (El Faouzi, 2010), as discussed in chapter 2.

Road accidents are typically a consequence of the combined effects of several different factors: (Leviäkangas et al. 2011)

1) behavioural
2) technological
3) environmental

Bad weather is one of the statistically significant accident risk enhancing factors. Because weather is only one of the factors that increase the risk of accidents, it is not straightforward that most of the accidents happen during adverse weather. It is nevertheless evident that adverse weather conditions contribute to elevated accident rates. For example, Juga et al. (2010) found that the extent of decreased visibility has a positive correlation with the collision rates in wintry conditions. However only about 45 % of accidents in Finland have taken place in the winter time.
which is approximately the same share as the share of winter driving in the total annual road traffic performance on roads. This could hint at a constellation where weather risk is a more important explanatory factor in winter time, whereas behavioural reasons dominate in summer condition. The same conclusion was found in a Finnish study that reported that in the summer time behavioural reasons (including driving on drugs or alcohol, over speeding and carelessness) are the most important factors leading to accidents (Rajamäki and Malmivuo 2008). As the adverse weather has a more important role as a risk factor in wintry conditions, the value of weather information is higher during the winter time thanks to its larger potential to reduce the accident rates.

Weather service value chain for vehicle drivers

There is a high availability of weather information for road-way users. In most countries the public has almost continuous access to weather information from a variety of sources like television, radio and internet. The availability rate is so high that in some studies (Lazo & Chestnut 2002) the public gave a negative value for more frequent weather forecasts. This would suggest that there is not much use for excessive information – at least from the traditional sources. Also the inaccuracy of the weather forecasts does not seem to be a major concern for vehicle drivers: for example a study in Canada in 2003 (Andrey and Knapper 2003) reported that a majority of Canadians were satisfied with the accuracy of road weather information and accuracy has only improved since then. A study in Finland (Sihvola et al. 2008) studied how accurate road weather forecasts had been. A warning for adverse conditions had been given prior and on almost all of the high accident-rate days (19 out of 21). Some room for improvement was found in forecasting the first and the last slippery conditions of the winter as they tend to surprise people and lead to more accidents than slippery conditions during the rest of the winter. In another study (Sihvola and Rämä 2008) only three percent of the drivers were disappointed by the quality of the weather information service. Andrey and Knapper (2003) even suggested that weather forecasts might be in fact ahead of their time and more emphasis should be put on the use of weather information e.g. in the vehicle drivers’ decision making.

Even though the availability of information is ample, road weather information reaches only about 60 % of the road users (Sihvola and Rämä 2008). According to the study, road weather information had usually been obtained from television or radio, internet gaining more and more important role as a source of information. 90 % of the road users were familiar with the road weather information services (Sihvola and Rämä 2008).

In fact one needs to be careful with the assumptions regarding the causal constellation, as we are dealing with complex embedded behavioural phenomena as well as a wide range of possible physical circumstances, some of them related to (other aspects of) weather. We know from e.g. Cools et al (2010) that avoiding trips is an important response in case of forecast bad weather. We also know that there is seasonal (precautionary) switching in mode choice (from road to transit in winter). If precautionary responsiveness is stronger in winter than in summer and if less experienced drivers only drive in summer, it may mean that up to now benefits of road weather service in summer remained largely untapped. Perhaps it needs a different set-up and focus in summer, e.g. anticipating on variations in driving skills and accounting for local intense thunderstorms, low angle of the sun in a cloudless sky and such like.
Also the timing of the weather information is important. Drivers request about 12 hour lead-times to be able to modify their travel plans. (WIST 2002) Accuracy of 12-hour forecasts is then the most important weather forecast quality factor that could create value by altering people’s decisions about their travel plans. Real-time information about the weather conditions is needed by the drivers to change their travel speed and sometimes route. Speed reductions are usually based on personal observations (Pisano and Nelson 1997), but personal observations about the current conditions are not always very accurate (e.g. Sihvola and Rämä 2008). Therefore there is potential for the road weather information service to increase its realized value by giving more information about site and time-specific weather conditions that affect vehicle handling, visibility and friction (Andrey and Knapper 2003).

Table 4.2 Drivers’ adjustment (modified Andrey and Knapper 2003)

<table>
<thead>
<tr>
<th>Timing</th>
<th>Adjustment</th>
<th>Relevant weather info</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before trip (previous day/evening)</td>
<td>Travel plans or modifications (cancellations, route selection, timing, mode, vehicle preparation)</td>
<td>short- and medium-term weather forecast, road weather forecast or previous evening</td>
</tr>
<tr>
<td>During the trip</td>
<td>Instantaneous driving decisions like speed reduction or longer safety margins</td>
<td>Site and time-specific weather conditions that affect vehicle handling, visibility and friction</td>
</tr>
</tbody>
</table>

As Bayesian decision theory suggests, information has value only if it has an effect on decision-making. In Sihvola and Rämä (2008), one fifth of the drivers had made or had considered making changes to their travel plans because of the weather forecasts. In an earlier study by Kilpeläinen and Summala (2002; according to Sihvola and Rämä 2008) 6 % of the respondents had actually changed their travel plans because of weather information. The respondents who had been actively following forecasts were more likely to modify their travelling decisions. Cancellations were not reported because the survey was conducted en route and the ones who had cancelled were not reached by either of the surveys. However, the volume of the traffic was significantly lower after forecasts of bad driving weather had been issued.

Weather information has also a significant effect on the driving speed. The ones who had obtained weather information beforehand drove on average 5km/h slower than the ones without weather information. One reason for this is that the ones without information evaluated road conditions to be much better than they actually were (Sihvola & Rämä 2008). Because of varying speed reductions, also the driving speeds vary more during adverse weather. This increases the risk for accidents. Thus, the benefit of getting more people better informed about the weather conditions would be even bigger than the lowered risks for the drivers who would reduce speeds after obtaining the information. It would lower the overall risk level in traffic - even for the ones that were already informed about the road conditions.
Table 4.3 Information filtering steps for vehicle drivers based on literature

<table>
<thead>
<tr>
<th>Information filtering steps</th>
<th>Present qualities and room for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 weather forecast accuracy</td>
<td>Accuracy levels good, 92% or 19 out of 21 bad weather days were predicted (Sihvola et al. 2008, in Finland)</td>
</tr>
<tr>
<td>2 information/message customer orientation</td>
<td>Road weather warnings are well understood by drivers – about 90% of people understand what is meant by “normal” “poor” or “very poor weather” (Quantis 2010), (Sihvola et al. 2008)</td>
</tr>
<tr>
<td>3 access to weather information</td>
<td>high availability, user rates however only about 62 % (Sihvola et al. 2008, in Finland) messages needed about current road weather conditions including in-car systems and road signs (WIST 2002)</td>
</tr>
<tr>
<td>4 comprehension of the information</td>
<td>People mostly use personal observations over real weather information (Pisano and Nelson 1997), bad judgements about current conditions However weather information makes the judgement about current conditions more accurate (Sihvola and Rämä 2008) – 85%</td>
</tr>
<tr>
<td>5 ability to respond timely and effectively</td>
<td>the frequency of bad weather warnings sufficient for timely responds (Lazo and Chestnut 2002) but too high threshold for adjustments (Pisano &amp; Nelson 1997), 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.</td>
</tr>
<tr>
<td>6 actual effectiveness of responses</td>
<td>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 bad weather warning issued (Quantis 2010 in Finland) – we give numerical value of 80%</td>
</tr>
<tr>
<td>7 incidence of the costs and benefits of the response</td>
<td>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</td>
</tr>
</tbody>
</table>

4.2.2. Bus and truck operations

The risks concerning bus and truck operations are almost the same as for vehicle drivers. However the information needs and utilisation differs from individual vehicle drivers’. Operators are more professional and use information more rationally. On the other hand, operators require longer lead-times to be able to change timetables or routes. WIST (2002) reported that requested lead time is 12–24 hours for bus and trucking operations (allowing operators to reschedule, reroute, postpone, or find safe-haven for vehicles and cargoes).
4.2.3. Road maintenance

Road maintenance includes winter road maintenance and maintenance of the road infrastructure year-round, like road surface damage repair. For road maintenance crews, accurate knowledge of the starting and ending times of winter precipitation event are crucial. First, the effectiveness of road surface treatments is highly dependent on the timing. Treating a roadway too early or too late can substantially reduce the effectiveness of the effort to reduce the threat to life or property. (WIST 2002) There are two critical lead times that road maintenance requires:

1) Longer time horizon - 24–48 hours for road maintenance operations (allowing time to begin the preparation process, predict the threatened area, select a treatment strategy, and prepare and deploy treatment asset) -&gt; longer lead-time -&gt; cost effectiveness

2) Shorter time horizon - The second lead time window of major value extends roughly from 0 to 6 hours before the adverse weather which is the execution phase of the road maintenance. For road maintenance, this means final decisions and initial operations to treat and clear roads of snow, ice, and debris; deployment of treatment crews and assets; and initiating changes in traffic flow management. This phase makes use of current observations, as well as near-term forecasts and observations.

The use of weather information is most crucial for winter road maintenance. The benefits of accurate weather forecast include effective use of personnel and chemicals and timely responds to weather events affecting road conditions. One of the often used examples is the decision whether to salt the roads or not. Examples follow the Cost-loss pattern demonstrated in 3.2.1. Cost in this case is the cost of salting the road and the loss is the failure to salt the roads when needed which results in higher level of accidents and sanctions for the maintenance company. Examples can be found in Thornes (2001) and Smith and Vick (1994).

Studies reach the same conclusion: costs of winter road maintenance are high, but the losses - due to inadequate maintenance like road closures and high level of accidents - are much higher. Accurate forecasts have potentially a significant value for winter road maintenance by both avoiding excessive costs and ensuring timely responses to adverse weather conditions. Berrocal et al. (2010) suggested that probabilistic forecasts are needed, because it is generally rational to take anti-icing measures even when the forecast probability of ice is well below 50%. This is because the losses of failing to take anti-icing measures when ice does form on the road are much larger than the costs of anti-icing when no ice forms.

A qualitative list of benefits of weather information for winter road maintenance is provided in a thorough study by Ye et al. (2009) from Iowa Department of transportation. Results were gathered from a large group of maintenance operators in USA and Canada and are presented in table 4.4.
Table 4.4 Benefits of using weather information for road maintenance (Ye et al. 2009)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>More timely and accurate response to winter storms</td>
</tr>
<tr>
<td>2</td>
<td>Better preparations for storms, including scheduling of crews and preparation of equipment</td>
</tr>
<tr>
<td>3</td>
<td>Improved roadway clearance time</td>
</tr>
<tr>
<td>4</td>
<td>Reduced use of chemicals and materials</td>
</tr>
<tr>
<td>5</td>
<td>Reduced labour costs, including overtime</td>
</tr>
<tr>
<td>6</td>
<td>More accurate staffing and budget plans for entire season</td>
</tr>
<tr>
<td>7</td>
<td>Reduced equipment usage and associated costs</td>
</tr>
</tbody>
</table>

As noted earlier, these benefits can be grouped to avoiding costs of excessive protection (reduced use of chemicals and materials, reduced labour costs, more accurate staffing, reduced equipment usage and associated costs, scheduling of crews – ranks 4,5,6,7 and part of 2) and to avoiding losses from inadequate protection (more timely and accurate response to winter storms, better preparation for storms, improved roadway clearance time – ranks 1-3).

Winter maintenance cost model

This model is presented in Ye et al. (2009). Their study is one of the best examples of studies concerning costs and benefits of forecast information for road maintenance activities. The model is presented here as an example how the benefits of weather forecasts can be evaluated.

Winter road maintenance costs refer to direct costs of materials, labour and equipment (sanctions of bad service level should be included) and other relevant cost factors. Their use is affected by many factors or inputs. So the costs are a function of the input factors:

$$WMC_k = f(LM_k, LOS_k, WSI_k, WI_k, AI_k),$$

$L_{W} = \text{length of roadway multiplied by lanes (lane mile or lane kilometer) maintained by unit } k$

$LOS_k = \text{level of service of the unit } k \text{ (contract issue, usually a pavement condition requirement)}$

$WSI_k = \text{winter severity index of the area maintained by unit } k$

$WI_k = \text{weather information usage, Ye et al. (2009) used discrete variables from 1-5 concerning the accuracy and the frequency of weather forecast usage by unit } k$

$AI_k = \text{the level of anti-icing used by maintenance unit } k$

Before the actual evaluation using the cost model, the input variables that are actually relevant for the study, need to be identified. Ye et al. (2009) use a two-step research methodology. A sensitivity analysis method is used to explore the effects of inputs to output based on a trained neural network model (another kind of regression might do the same trick, where the significance of parameters would be tested with t-tests). After this phase relevant inputs are kept at their mean levels and weather factors are allowed to change, changes of output are again evaluated with the help of neural networks (or different regression techniques).
Sensitivity analysis is a method to study how uncertainty in the model output is attributed to different sources of variation so that the objective is to find the inputs that are most responsible for the output variation. Output and input data need to be scaled before the actual analysis. One of the methods for scaling is minimum-maximum method. After scaling the sensitivity analysis is done with the following phases:

1) mean and standard deviation for each variable is calculated
2) for $x_1$ evenly divide the interval of $\left( (\bar{x}_1 - \sigma(x_1), \bar{x}_1 + \sigma(x_1)) \right)$ into $k$ sub-intervals (or input values) of $x_1^1, \ldots, x_1^k$
3) calculate results of $y_1^1, \ldots, y_1^k$ keeping other inputs fixed at their means
4) analyse sensitivity of $x_1$ by using partial derivate technique $S_1 = \frac{\partial y_1}{\partial x_1}$, which can be approximated by using Taylor series approximation and calculating average sensitivity
5) Repeat steps for other input variables
6) Obtain sensitivity for all variables and normalize sensitivity values

After identification of key input variables the impacts of weather information on the maintenance costs can be evaluated. Analysis will be done again but only for weather variables by keeping the other variables fixed to their means. Only steps 1, 2 and 3 are needed to evaluate how different levels of weather information affect the overall costs of maintenance.

Ye et al. (2009) made three case studies with the quoted method and found that costs decrease approximately linearly with the improvement of weather forecast accuracy level. Increase in frequency reduced the costs at low frequency levels, but cost curve became flat (no decrease in costs) when the frequency reached a certain level. This is in line with other studies such as Lazo and Chestnut (2002). The benefit-cost ratios Ye et al. (2009) found with the case studies are presented in table 4.5. Benefits only include agency benefits and estimates are thus very conservative.

<table>
<thead>
<tr>
<th>Case Study State</th>
<th>Winter Season</th>
<th>Winter Maintenance Cost ($'000s)</th>
<th>Benefits ($'000s)</th>
<th>Weather Information Costs ($'000s)</th>
<th>Benefit-Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa</td>
<td>2006–07</td>
<td>14,634</td>
<td>814</td>
<td>448</td>
<td>1.8</td>
</tr>
<tr>
<td>Nevada</td>
<td>2006–07</td>
<td>8,924</td>
<td>576</td>
<td>181</td>
<td>3.2</td>
</tr>
<tr>
<td>Michigan</td>
<td>2007–08</td>
<td>31,530</td>
<td>272</td>
<td>7.4</td>
<td>36.7</td>
</tr>
</tbody>
</table>

Extended asset management systems

The task of road maintenance is to ensure a minimum level of service (with traffic flow and traffic safety as principal factors) throughout the road system while keeping current and expected costs manageable, and honouring side conditions, e.g. regarding environmental requirements. Maintenance can encompass smaller repairs due to winter damage, as well as larger refurbishments and adding of lanes. Road clearing (from snow and debris) is usually seen as an operational task, separate from other maintenance. Since implications of climate change may vary...
across locations the preventive responses need to be flexible in order to enable least cost solutions. As a consequence asset management tools (including indicators for the technical state of road sections) will be very valuable and merits to be adapted so as to include the implications of climate change (Meyer et al. 2009). In turn the further development of these systems to adequately account for climate change needs often rather detailed technical research (Petkovic et al, 2010; IRWIN 2009). Judgment of effects and prioritization of actions will also depend on the way road and maintenance is funded (from the annual budget; from a fund; through public-private partnership PPP) and whether some kind of lifecycle costing approach is allowed in the evaluation of how to prioritize maintenance needs.

The maintenance task interacts with operational tasks (like snow clearing) and strategic tasks (road planning). Budget pressures in one task group may lead to cost rises in another. For example, some asphalt types may require more often salting against slippery conditions than other ones. On the other hand experiences in each of the task groups could also be used to make activities and choices in another task group more effective. It means that learning across the entire road administration is important.

The share of the annual budget of the Finnish Transport Agency attributed to maintenance of roads is about 550 million euro, of which operational tasks may cover up to 10% of that budget. The investment amount for new roads is about the same as the maintenance budget. The relative significance of the maintenance budget will rise as investment in new roads will stagnate or decrease. The total value of the Finnish road system is in the order of magnitude of 36 billion euro (representing the approximate current replacement value; Uimonen 2008).

In road planning and maintenance service level is an important lead concept, denoting primarily standards for traffic flow, average speed, and safety by road type and segment. Observed traffic flows, speeds and accidents can be compared with minimum target levels. If minimum target levels are too often not fulfilled action should be taken. By means of operational and maintenance services a road administration attempts to manage the road system such that below target achievement remain a marginal phenomenon, though without incurring too much cost. The challenge is to find a robust balance between current quality and cost demands and future quality and cost demands. To this end the road administration is monitoring traffic flows and accidents on its network as well as running an asset management system, which also includes indicators for the technical state of the roads (by segment). It buys weather information to project needs for clearing services and quick repairs, as well as provide services for road users informing them via internet cameras regarding the driving conditions of road segments. It may also operate electronic speed indication systems, e.g. in case of adverse weather conditions, congestion, etc.

Despite these extensive observation systems the experienced service level of drivers may deviate from that defined by the road authority. One approach is to use feedback surveys among road users (Lodenius 2011), which are used in almost all Nordic countries. However, these surveys are held at most once a year and often even less frequent. So, these surveys are picturing posterior impressions of states and tendencies in traffic. Furthermore, the surveys may – at least in part – measure acceptability levels instead of potentials for improvement. This still can assist in priority setting of maintenance and correction of some road maintenance practices, but it misses opportunities for improving proactive management.
4.3. **Rail transport**

Different kinds of weather events can have a major influence on railroads. Weather can affect operating efficiency, physical infrastructure and safe passage of freight and people. Despite the current level of weather information, weather events still cause major problems for railroad operators. For example, the Finnish Minister of Transport and Communication demanded an explanation from Finnish Transport Agency (responsible for rail maintenance) and from VR Group (Finnish train service operator) of the problems Finnish railroads encountered in winter 2010. The report stated that the main reason for delays (28 percent of long haul trains and 19 percent of short haul trains were late from November to December 2010) was harsh winter and accumulation of snow. Harsh winter conditions caused failures of equipment. The report also stated that snow removal was on a better level than a winter before – obviously problems still occurred. The costs of snow removal are between 20 to 30 million euros depending on the winter (VR 2011). The report also stated that long-term investments are needed, which should use climatic information as a decision-making tool.

In the UK, Thornes (1992) raised a question whether climatic design of railway equipment had been good enough. He wondered why no lessons had been learned from January 1987 snow chaos in the UK and why another chaos had taken place in 1991. A similar example of – perhaps bad decision making exists in Finland from the year 1992 when the national railroad company VR decided to order Italian trains instead of trains designed for northern conditions. The trains in question have been very unreliable, especially in the winters. The use of climate data is essential in the planning of long-term investments and failure to adjust decisions to climate data can cause extra costs and losses over a long period.

Railroads rely on a number of meteorological services. Rossetti (2005) lists several weather forecast attributes and ways how they can help decision makers in the railroad community. Benefits arise from better decisions in go/no-go situations, scheduling, estimation of delays, passenger information system, operational improvements, routing, timing connections for intermodal transfers, relocation of railcars and staging equipment etc. Benefits include higher efficiency (better allocation of work force, reduced work hours, better investment decisions) and better customer satisfaction (better information about the trip, fewer delays and enough space on the railcars).

In 2005, NOAA sponsored a study to estimate the value of selected NOAA products within the railroad sector. Railroad companies used a vast array of NOAA’s products, including local climatological data and surface weather observations. Weather information was used in strategic, tactical and operational decision making. Long-term decisions - that relied on climatological data – included planning of construction and weather hazard prediction as a way to improve safety. Operative decisions included scheduling of trains, local operations and traffic disruption minimization in the case of weather extremes. One important user group of weather information in the railroad companies was the legal department which acquired historical data either to determine weather conditions for specific times or to verify a claim made by another party (NOAA 2005).
The study used an opportunity cost based method, called the Alternative Cost Approach. The method is based on the estimation of the general costs of establishing and operating a system that would provide the same weather information that were obtained from NOAA at the time of the study. This cost is then considered as the benefit of NOAA products. However, it is forgotten in the study to mention, that some of these products would probably not be acquired at all in case of higher purchase costs. The study estimated that total cost of maintaining products and services is 10.8 million dollars a year for the five big railroad companies while they pay on average (a mere) 825 dollars a year for the current services to NOAA. Total benefits for the Class 1 freight railroad sector was estimated to be 11.5 million dollars a year (NOAA 2005).

SwissMeteo has also carried out and commissioned research regarding the value of weather information for transportation sectors (as well as other sectors). They report that because railroad network is less dense to weather than road network, also the potential value of weather information is lower. The benefits of weather information are limited to a rather low number of episodes per year. Calculated benefits based on the alpine tracks are: 0.3 to 0.4 Mio CHF/y. The estimates are based on stakeholder interviews (Willemsse 2011). The relatively low numbers may reflect a very high level of coping capabilities of the Swiss railways as regards adverse weather (and hence may be not indicative for European railways in general).

4.4. **Maritime ship transport**

A very large number of activities are included in the maritime sector. These activities are either directly or indirectly linked to maritime ship transport. Ship transport may be for commerce, recreation, military or rescue missions. The fluency of the transport has direct effects on the whole maritime cluster and indirect effects to the whole society. The magnitude of the sector reveals that even small changes in the efficiency of the actual transport may have strong economic impacts and the improvements in the weather services can potentially create a lot of benefits. The direct added value of the maritime sector in Europe (2008) was almost 200 billion Euros. The indirect effects to other sectors are obvious since the majority of the cargo trade is handled by the ship transport sector. (Policy Research Corporation 2008)

Apart from obvious sensitivity to most extreme weather events - which may cause even catastrophic losses – all vessels are sensitive to weather variation. Weather can have an effect on stability, journey time, safety of the cargo and vessel, fuel efficiency and cargo load. Commercial shipping includes many layers of decision-making as well as different sources of weather information. Ship owners are usually companies that own more than one ship. They are responsible for taking the orders, making timetables and running the companies. Usually they hire a captain and a crew for the operational shipping process. As the shipping company is responsible for the strategic level decision-making, the captain makes tactical level decisions when it comes to safety, management of the personnel and other operational tasks. The weather information that is needed and used is different for different layers of users. Strategic level decisions require long-term weather forecasts (such as climate models that affect the choice of the ship type) whereas tactical level decisions rely more on short-term forecasts or nowcasts. The requirements for the weather information on a tactical level include: actual weather during the
transport, predicted short and medium term weather, oceanographic conditions, wind and sea state information including wave information and some other information types such as visibility, air pressure, cloud cover, water level and current information and forecasts. (Cyprus Meteorological Service).

The benefits of weather forecasts include improved safety and better efficiency. The savings in operating costs derive from reductions in heavy weather encounters. Savings are achieved by reduction in transit time, fuel consumption, material and person damage and more efficient scheduling of dockside activities. Another benefit from weather forecasts is the optimized loading of vessels (Kite-Powell, 2010). On a longer scale these benefits result to fewer repairs to the ships, more efficient use of personnel, lower insurance rates and better customer satisfaction as deliveries are made in time. Benefits arise thus from higher valued products and lowered costs.

Quantitative studies related to the value of maritime weather forecasts are relatively scarce. Craft (1998) studied the effects of storm-warnings to the losses encountered by great-lake shippers in the 19th century. Budget reductions in the Army Signal Service’s weather activities in 1883 led to the reduction of fall storm warning broadcast occasions on the Great Lakes from 80 in 1882 to 43 in 1883. This drop creates a special opportunity to measure the value of warnings of extremely high winds on the Great Lakes by a natural experiment method. As there are many other factors besides the warning system that affect the losses, a regression was estimated between the relevant factors – including the number of storm warning occasions – and the actual losses. Other factors held constant, Craft concluded that each extra storm warning occasion on the Great Lakes lowered losses by about one percent. He also backed up his results with an indirect method: Shipping prices on the high-storm risk season should rise to reflect the additional risk when the storm-warning system was downsized. Such change in shipping prices due to extra losses caused by storms can be differentiated from other types of technological improvements by studying how the shipping prices in the fall changed relative to the summer shipping prices. Most of the weather related losses took place in the fall. This method supported the conclusion that storm warnings were valuable and the results are consistent with the direct natural experiment method (Craft, 1998).

Other valuation studies include a report from International Maritime Organization (2000), a study of greenhouse gas emission from ships, which estimates that fuel consumption could drop by 2-4% with effective weather routing. The number is actually based on a Norwegian study (only in Norwegian) by Lepsoe (1997). In the United States Kite-Powell has studied the economic values of different weather products for different maritime users in several studies (e.g. Kite-Powell, 2010), most of them sponsored by NOAA. He has given order of magnitude estimates for different users within ship transport industry for different NOAA products.

The route choice

Most of the mentioned benefits are relate to optimized route choice. As the shipping industry is highly competitive and the logistic products are nearly homogenous, cost effectiveness is an important competition factor. One way to improve cost effectiveness is to improve the use of weather information in the decision making process.
One example of the use of weather information in the route choice is provided by Leviäkangas et al. (2007). The example is based on the Cost-loss model and the decision is whether to use the channel of Kiel or sail through the straits of Denmark when sailing out of the Baltic Sea. Sailing through the straits is cheaper than using the channel in good weather conditions. In a case of high winds the trip through the straits takes very long and a lot of fuel is consumed which results in losses. Sailing through the channel is expensive but the outcome is certain. Cost table is as follows:

Table 4.6 Cost-loss for a route choice

<table>
<thead>
<tr>
<th>Action</th>
<th>High winds</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel (protect)</td>
<td>Cost of the channel charges</td>
<td>Cost of the channel charges</td>
</tr>
<tr>
<td>Straits (no protection)</td>
<td>Loss of fuel, delays, decreased safety</td>
<td>0</td>
</tr>
</tbody>
</table>

The choice which route to choose is based on forecast information. As explained in chapter 3.2.1, after a certain threshold better forecast accuracy creates value by avoiding unnecessary mitigation costs and/or avoiding losses. Of course this example is again a highly simplified version of the reality. There's a variety of consequences and weather conditions and the route choice is not usually a choice between only two but rather an endless number of alternatives.

The Cyprus Meteorological Service has conducted interviews with ship owners. Interviews revealed that there exists demand for wave models, fuel consumption models and best available route models. The shipping sector is an extremely competitive field and ship owners need to aim at the best cost-effective scenario to stay viable. The inability of national meteorological organisations to offer these kinds of services has created a trend in which private corporations are supplying these services to shipping companies. On the competitive market, the prices are reflecting the value of these services.

An example of these products is a service called weather routing which exists to help decision-makers in the route choice. It is a numerical procedure which attempts to find the best possible route when the costs of delays and fuel consumption are known. It combines weather forecasts with polar charts and compares millions of different route choices. The initial route recommendation is based on a weather forecast at the time of the initial decision. A ship's progress is constantly monitored and if adverse weather is forecast along the current route, a recommendation for a route diversion is given for the vessel. The largest benefit of ships' weather routing is attained when the passage is relatively long and waters are navigationally unrestricted. Normally two kinds of services are provided: 1) a technique to forecast conditions and compute routing recommendations and deliver the recommendations to the ship or 2) a service to assemble and process weather and sea condition data and transmit this data to the ships. The former option might have an advantage, because of greater computer power used in route choice while the latter system allows greater flexibility for the captain. Ship routing services are offered by many nations, including United Kingdom, Russia, Netherlands, Germany, Japan and United States. Yet, as mentioned, many private firms have engaged these markets as well. One example of such a firm is MeteoGroup (www.meteogroup.co.uk) which offers a wide array of weather services for business users.
4.4.1. Ports

Ports work as nodal points connecting maritime activities to other sectors by interconnected motorways and railroads. Cost and efficiency of the ship transport depend not only on the performance of the actual shipping, but also on the port efficiency in loading, unloading and forwarding the cargo to its final destination. Seaport efficiency is important in the maritime supply chain and for the competitiveness of the sector. Any factor that hampers the loading of goods and passengers has a potential of creating delays and thus affecting the whole chain of the movement of the cargo (Trujillo and Nombella, 1999). These factors include different weather phenomena. Extreme weather events can create congestion and delay the movement of the cargo. Also material losses are possible, since cargo is exposed to high winds and storm surges in trans-shipment facilities. Ports use weather services in three different time scales of the risk assessment process: on the day assessment and decision making using real time monitoring of the weather, short and medium term assessment using weather forecasts and in the long term assessment using climate modelling. (Cyprus Meteorological Service). This is illustrated in figure 4.2.

**Figure 4.2** Relationship between short, medium and long term planning and the use of weather information

Weather forecasting particularly meant for seaports is mainly based on national weather forecasts (for day-to-day operations) and research related to future weather conditions and climatology of the area (in order to deal with upcoming trends). Forecasts are important for day-to-day operations since port authorities are directly responsible for the general well-being of a ship in the port and of the regulative matters such as whether a ship is allowed (or not) to disembark due to weather conditions in the open sea, and take preventive measures to reduce accident probabilities in case of adverse weather (such as halting on going port operations or issue alerts).
Many operations such as vessel operations, subsea operations within a port (diving), crane lifts, ship loading involve coupling of structures or unevenly distributed weighting. These constructions are particularly at risk from unacceptable motions initiated by waves which can lead to impacts and even capsize events. The efficiency and correct implementation of such measures are directly connected with the availability and reliability of weather forecasts, their timely dispatch and correct assessment. Economic losses can be profound in the case of incorrect or late arrival of vital weather information that can result in port congestion, unnecessary halting of operations, delays, damage to ships and various other impacts (Cyprus Meteorological Service).

4.4.2. Ice breaking

Icebreaking is vital for the shipping industry in the Baltic Sea. Ice breakers are needed to keep waterways open. Icebreakers are very expensive to build and very expensive to run. In Finland Arctia Shipping is the biggest operator in the icebreaking industry. As they are planning their billion euro investments of new icebreakers it is crucial to know how the ice conditions are going to change in the Baltic Sea area. This is an example how even very long term forecasts or estimates based on climatological studies can have a large value as they help decision makers to make profitable investments. For example, Arctia Shipping ordered an estimate of the ice conditions until 2050 from the Finnish Meteorological Institute (Muukkonen 2011).

Winds have an effect on the movement of sea ice. They can create open waterways for the ships or create big dams of ice that prevent ships from using their regular routes. Ice breakers take advantage of weather information when informing ships about open waterways and in their own actions and route planning. With the wind forecasts ice breakers can open the essential waterways. However the ice breaking capacity is limited and the most important thing is to direct the ships to the available passages. (Leviäkangas et al., 2007). Meteorological services are of high importance in these activities and the present system could not exist without those services. The monetary value of weather services with respect to ice breaking activities has not been assessed at all so far. While the costs of ice breaking in the Baltic Sea area can reach almost 100 million euros a winter (Baltic ice breaking management, 2010), the costs vary heavily from winter to winter and the industry relies heavily on the meteorological services. Hence, better forecasts have a substantial potential to create more value.

4.5. Light traffic

Light traffic (i.e. non-motorized transport modes like walking and biking) is a transport mode that has not received as much attention in relevant research as other modes (Leviäkangas and Hietajärvi 2010). However, the costs of falling accidents due to slippery pavement are huge in Nordic countries and the mode should not be ignored. The relevant question is to ask how much accident costs are avoided with weather information and how much could be avoided with better weather services. Not many estimates exist in the current literature, the only estimates are found from a Finnish study which made a cost/benefit analysis on the services provided by Finnish meteorological institute (Leviäkangas et al. 2007).
The Finnish Meteorological Institute (FMI) has developed a special weather service for pedestrians in order to prevent wintertime injuries due to slippery pavement conditions. Meteorologists forecast the pavement condition using three categories: normal, slippery, and very slippery. Upon very slippery conditions a warning is issued. The service is the first of its kind in the world (Flinkkilä et al., 2010). Leviäkangas et al. (2007) concluded that about 7% of slipping accidents are currently avoided with the use of weather information. The same study estimated – with a reference to another study by Aittoniemi (2007) – that the maximum amount of avoided slippery accidents with better weather information would be 18%. Part of the benefits stem from better maintenance services and part from more informed decisions of pedestrians and cyclists. Better decisions include the choice of footwear, the time of the trip, route choice, mode choice (for example between walking and cycling) and the planned travel time.

During wintertime pavement conditions in Finland are often snowy and icy and therefore hazardous. Around 70,000 slipping and falling accidents take place outdoors leading to serious consequences. About two third of these accidents occurs in slippery conditions, which means about 50,000 slipping accidents during wintertime and an incidence of around 1/100 in the Finnish population (Ruuhela et al. 2005a). Similar results are found from Sweden (Leviäkangas et al. 2011). The costs of these accidents were estimated to be around 2.4 billion euros per year (Leviäkangas et al., 2007) in Finland. The high level of accidents costs creates a huge potential for meteorological services. Leviäkangas et al. (2007) estimated that only in the Finland, the value of weather information for this purpose is around 170 million euros per year (calculated with a 7% drop in accidents thanks to focused meteorological services).

For both pedestrians and cyclists the most slippery conditions occur during the days when the temperature is close to zero degrees Celsius. There is a statistical correlation among these days and the number of slipping accidents per population (Ruuhela et al., 2005b; Flinkkila et al. 2010). With the use of this correlation, a crude estimate of slipping accidents among any region could be found. Other harmful phenomena include strong wind, strong precipitation and extreme temperatures (Leviäkangas et al. 2011). No statistical data about falling accidents could be found at the European level.
5. Compilation of literature review

5.1. **Valuation methods**

There are several options to assess the value of weather service in relation to transport based on the literature review:

1. **Transport system simulation model** (e.g. Lam et al. 2008)
   - trip generation per day (weather conditions may give rise to skip, reschedule, or initiate trips)
   - trip timing and mode choice
   - vehicle occupation / utilization rate
   - resulting traffic intensity and speed per infrastructure segment
   - collision probability and impact per segment

   If travellers’ and shippers’ preferences in the subsequent steps are (approximately) known in normal and non-normal weather conditions the impact of more accurate or earlier available weather information on (a segment of) a transport system can be simulated in a network flow model. Assumptions about 100% rational users and 100% access can be relaxed to get some notion of the influence of the intermediate information steps. This approach would be greatly enhanced when it can be validated with complementary research, i.e. questionnaire based surveys (option 2) and natural experiments (option 3).

2. **Questionnaire based survey** (e.g. Lazo and Chestnut 2002).
   - what – if questions, asking for type of response in particular situations
   i. can refer to actual experiences ('revealed preference'); or to
   ii. supposed responses ('stated preference');
   iii. a special case is to test ‘willingness-to-pay’ (WTP)
   - background information of the respondents

   This approach allows for more detail regarding response type/strength by user type and/or trip purpose. However, in case of stated preferences (and sometimes also revealed preference) less reliable information and/or selectivity bias regarding the group that is willing to answer the questionnaire (as compared to the entire user group).

3. **Natural experiment** (e.g. Klein et al. 2009; Craft 1998).
   - compare announced (forecast) adverse weather events and surprise events in terms of possible differences in responses
• compare old and new service level periods for a given segment of a transport system
• other factors (such as transport technology, traffic patterns, traffic rules, age and driver skill structure, etc.) should be as much as possible be the same in the ex-ante and ex-post situations
• need sufficient numbers of observations (which may be difficult to match with the desire to keep other factors constant)

4. Downscaling from retrospective macro-analysis
• by comparing countries with different weather service levels or comparing developments over time in the same country and check for differences in productivity by sector some crude estimates of the macro-economic contribution of weather services can be obtained

5. Simple changes in accident rates (e.g. Leviäkangas et al. 2007)
• on the basis of expert opinions an impression of the order of magnitude of the responsiveness to new (extra) information can be obtained; subsequently a reduction in expected accidents and consequent direct cost savings can be calculated.

6. Broader production function approach (e.g. McCrea et al. 2007)
• in which weather forecast just one factor, but at the same time infrastructure, vehicle technology, and logistics develop as well, emphasizes interactivity of overall production/transport system (i.e. specific and shared benefits; see also section 2.2)

7. Opportunity costs (NOAA 2005; Leviäkangas et al. 2007)
• assessing the costs of companies or individuals performing weather information functions on their own as an alternative to acquire them

8. Simple Cost-Loss model (e.g. Leigh 1995; Smith and Vick 1994)
• as described in chapter 3.1.1, possible costs and losses estimated with a number of ways
5.2. Estimated values from the literature

Table 5.1 Literature overview

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>Forecast characteristics</th>
<th>Estimated value</th>
<th>Structure of decision problem</th>
<th>Valuation method</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation, Qantas Airways</td>
<td>Terminal aerodrome forecasts</td>
<td>1% increase in accuracy 1.2 million/year for Sydney airport Imperfect forecast 6.9 million/year for Sydney Perfect forecast 8.5 million/year for Sydney National value 16 millions (currency 1994 Australian $)</td>
<td>whether to carry extra fuel or not</td>
<td>Cost-loss</td>
<td>Leigh (1995)</td>
</tr>
<tr>
<td>Aviation, USA</td>
<td>NOAA (2005) reported 250 million dollar potential savings/year from improved ceiling forecasts</td>
<td>strategic level flight planning</td>
<td></td>
<td></td>
<td>McCrea et al. (2007)</td>
</tr>
<tr>
<td>Winter road maintenance</td>
<td>daily forecasts of precipitation occurrence</td>
<td>23,000 (1994 UK ) per 100 days winter maintenance per year, single region in Scotland</td>
<td>whether to apply de-icing materials or not</td>
<td>Cost-loss</td>
<td>Smith and Vick (1994)</td>
</tr>
<tr>
<td>Shipping, (19th century)</td>
<td>storm warning</td>
<td>each extra storm-warning location on the Great Lakes lowered losses by about one percent</td>
<td>how to prepare for storms or high winds</td>
<td>Natural Experiment</td>
<td>Craft (1998)</td>
</tr>
<tr>
<td>Several transportatio n modes</td>
<td>Weather information and services provided by Finnish Meteorological Institute</td>
<td>Road transport: 11-20 million (2005) €/year, potential for extra 9-18 million €/year Ship transport: 25-39 million €/year Aviation: 54 million €/year, potential for extra 4€/year Rail transport: 0.3 million €/year, potential for extra 0.2 million €/year Light traffic: 113 million €/year, potential for extra 162-243 €/year</td>
<td>Mainly questionnair e based surveys, simple changes in accident rates or downscaling from macro-analyses</td>
<td></td>
<td>Leviäkangas et al. (2007)</td>
</tr>
<tr>
<td>Rail transport</td>
<td>Selected NOAA products</td>
<td>11.5 million US 2004 dollars a year for the rail freight sector</td>
<td>opportunity costs</td>
<td>NOAA (2005b)</td>
<td></td>
</tr>
<tr>
<td>Marine transport</td>
<td>computer aided services</td>
<td>estimates that fuel consumption could drop 2-4 % with effective weather routing</td>
<td>use of computer aided weather routing systems</td>
<td></td>
<td>Lepsoe (1997)</td>
</tr>
<tr>
<td>Transport mode</td>
<td>Forecast characteristics</td>
<td>Estimated value</td>
<td>Structure of decision problem</td>
<td>Valuation method</td>
<td>Source</td>
</tr>
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<td>-------------------------------</td>
<td>------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Road transport</td>
<td>Road weather information service</td>
<td>The total cost impact on travel time, predictability, safety, valuations and comfort of the current road weather information service is 13,255,000 (2009) €</td>
<td>the effect of weather forecasts on travel decisions</td>
<td>changes in accident rates</td>
<td>Innamaa et al. (2010)</td>
</tr>
<tr>
<td>Several transport sectors</td>
<td>value of weather information, limited to the benefit to private companies and state-owned institutions in Switzerland</td>
<td><strong>road winter services</strong> total benefit 44 to 50 Mio CHF/y <strong>haulage contractors</strong> of 0.11 to 0.57 Mio CHF/y <strong>public road transport</strong> total benefit of 21.6 to 29.2 Mio CHF/y <strong>rail transport</strong> benefit (based on the alpine tracks): 0.3 to 0.4 Mio CHF/y, <strong>airport winter services</strong> estimate of the benefit 1.4 to 2.5 Mio CHF/y <strong>aviation benefit</strong> from the TAFs 20 Mio CHF/y</td>
<td>expert interviews</td>
<td>Willemsen, Saskia (2011)</td>
<td></td>
</tr>
</tbody>
</table>
6. Application of valuation methods

6.1. Case study, Finnish road transportation accidents

6.1.1. Introduction to the data

The data in the first case study are from the Finnish Motor Vehicles Insurer’s centre. It has all the accidents recorded per day by region from 2000 to 2009. Accidents are classified into different accident types. In this study we use the classification into accidents with and without casualties. From the Finnish Meteorological institute we obtained data about road weather warnings (by date and region) for the relevant years. Road weather warning levels are coded as 1 for normal weather, 2 for poor and 3 for very poor weather. Warnings are given only in the winter season, which stretches in this context over 200 days from October to March. By combining accident and weather warning data sets, we created a new data set with the accident and road weather warning information.

First, we tried to evaluate the amount of accidents on an average day with and without adverse weather with a method called *natural experiment*. As an indicator of days without adverse weather, we had road weather warning set as 1 on the actual day and on the evening before the day. We concluded that there were no cases in which days with bad or very bad weather were not accompanied by issued warnings on the previous or same day. Also Sihvola et al. (2008) wrote that no such days were found in their study, where the weather had been poor but no warnings were given.

By this way, about half of the days in winter time were labelled as days with normal driving conditions, with the exact share varying over municipalities. As 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. The share of normal weather could have been higher, but we were conservative as regards labelling days as normal. Only days with no road weather warnings on the day or evening before were accepted. By this way we wanted to ensure that bad weather was not a reason for the accident rate we estimated to occur normally (no bad weather). We estimated the average accident rate on days with normal weather. This accident rate is our estimate of road accidents on an average day that have no relation to adverse weather conditions - this accident rate is not dependent on the weather as the weather was normal in the whole sample. We conclude that this is the average amount of road accidents per day in winter time for other reasons beside poor weather. These estimates are shown in table 6.1.
Table 6.1 Average number of accidents per day in normal weather conditions

<table>
<thead>
<tr>
<th>Province</th>
<th>Average of all accidents</th>
<th>Average of accidents without casualties</th>
<th>Average of accidents with casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etelä-Karjala</td>
<td>5.6</td>
<td>4.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Etelä-Pohjanmaa</td>
<td>8.5</td>
<td>7.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Etelä-Savo</td>
<td>6.5</td>
<td>5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Häme</td>
<td>7.2</td>
<td>6.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Kainuu</td>
<td>3.7</td>
<td>3.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Keski-Pohjanmaa</td>
<td>3.1</td>
<td>2.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Keski-Suomi</td>
<td>10.7</td>
<td>9.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Kymenlaakso</td>
<td>7.7</td>
<td>6.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Lappi</td>
<td>10.7</td>
<td>8.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Pirkanmaa</td>
<td>19.5</td>
<td>17.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Pohjanmaa</td>
<td>8.3</td>
<td>7.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Pohjois-Karjala</td>
<td>6.4</td>
<td>5.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Pohjois-</td>
<td>17.1</td>
<td>14.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Pohjanmaa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pohjois-Savo</td>
<td>11.0</td>
<td>9.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Päijät-Häme</td>
<td>9.1</td>
<td>7.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Uusimaa</td>
<td>73.9</td>
<td>67.0</td>
<td>6.9</td>
</tr>
<tr>
<td>Varsinais-Suomi</td>
<td>21.0</td>
<td>18.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Whole country</strong></td>
<td><strong>230.0</strong></td>
<td><strong>201.3</strong></td>
<td><strong>28.7</strong></td>
</tr>
</tbody>
</table>

Next, we calculated the average accident rates on days with poor weather. A day was classified as having poor weather when at least one of the warning levels concerning that day was at least 2. This is a rather conservative approach, implying that days are relatively easily classified as ‘bad weather day’.

We calculated the average accident rate for those ‘bad weather’ days. The 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 between these days. However the analysis is done with calculations which include all poor weather days. The accident rates were significantly higher in each municipality than on the days with normal weather conditions. Also the level of accident without casualties had gone up much more than the rate of accident with casualties. This is in line with current theory. The resulting reduction in traffic intensity and traffic speed decreases the share of severe accidents, but slippery roads on the other hand increase the frequency of accidents. (Cools et al., 2010). The difference in accident rates between “normal weather days”
and “poor weather days” is what we concluded to be the number of accidents due to adverse weather conditions. This difference in each municipality is displayed in table 6.2.

Table 6.2 Difference in the average number of daily accidents by region between a day without bad weather and a day with (very) bad weather

<table>
<thead>
<tr>
<th>Province</th>
<th>Increased number of accidents per day</th>
<th>Increased number of accidents without casualties</th>
<th>Increased number of accidents with casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etelä-Karjala</td>
<td>2.0</td>
<td>1.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Etelä-Pohjanmaa</td>
<td>1.9</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Etelä-Savo</td>
<td>1.4</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Häme</td>
<td>1.9</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Kainuu</td>
<td>0.5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Keski-Pohjanmaa</td>
<td>0.8</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Keski-Suomi</td>
<td>3.0</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Kymenlaakso</td>
<td>1.5</td>
<td>1.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Lappi</td>
<td>1.1</td>
<td>1.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Pirkanmaa</td>
<td>4.8</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Pohjanmaa</td>
<td>1.9</td>
<td>1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Pohjois-Karjala</td>
<td>1.1</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Pohjois-Pohjanmaa</td>
<td>2.2</td>
<td>1.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Pohjois-Savo</td>
<td>2.2</td>
<td>1.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Päijät-Häme</td>
<td>2.4</td>
<td>2.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Uusimaa</td>
<td>14.2</td>
<td>13.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Varsinais-Suomi</td>
<td>3.9</td>
<td>3.7</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Whole country</strong></td>
<td><strong>46.8</strong></td>
<td><strong>42.5</strong></td>
<td><strong>4.0</strong></td>
</tr>
</tbody>
</table>

From table 6.2 can be read that for Finland as a whole on each day with adverse weather conditions there are on average about 47 accidents more than on a day without bad weather. 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 (Bläsche et al., 2011). We should point out that this 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,

\[ 52\% \text{ of the winter season } \times 46.8/230 = 10.5\% \]

71/92
the increased accident rate is the reduction potential left for improved winter weather information. Other accidents besides the accidents due to bad winter weather are out of scope of 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 is linked to other factors such as alcohol use, local road conditions, etc. (see also footnote 7, page 51).

For quantification of the monetary impact of increased accident levels on days with bad weather, we use data from the Finnish Transport Agency (Tervonen and Ristikartano 2011). The 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 493 000 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 service. It should be realized that these cost figures are composed of elements of a very mixed nature and therefore straightforward comparisons to some sector’s output or GDP are rather to be avoided.

Table 6.3 Average accident costs due to adverse weather in the winter season in Finland

<table>
<thead>
<tr>
<th>Province</th>
<th>Total accident costs (million euros)</th>
<th>Costs of accidents without casualties (million euros)</th>
<th>Costs of accidents with casualties (million euros)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etelä-Karjala</td>
<td>7.9</td>
<td>0.5</td>
<td>7.4</td>
</tr>
<tr>
<td>Etelä-Pohjanmaa</td>
<td>21.4</td>
<td>0.4</td>
<td>20.9</td>
</tr>
<tr>
<td>Etelä-Savo</td>
<td>7.3</td>
<td>0.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Häme</td>
<td>16.8</td>
<td>0.4</td>
<td>16.3</td>
</tr>
<tr>
<td>Kainuu</td>
<td>2.0</td>
<td>0.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Keski-Pohjanmaa</td>
<td>5.5</td>
<td>0.2</td>
<td>5.3</td>
</tr>
<tr>
<td>Keski-Suomi</td>
<td>22.5</td>
<td>0.7</td>
<td>21.7</td>
</tr>
<tr>
<td>Kymenlaakso</td>
<td>5.2</td>
<td>0.4</td>
<td>4.8</td>
</tr>
<tr>
<td>Lappi</td>
<td>-0.5</td>
<td>0.3</td>
<td>-0.8</td>
</tr>
<tr>
<td>Pirkanmaa</td>
<td>28.6</td>
<td>1.2</td>
<td>27.4</td>
</tr>
<tr>
<td>Pohjanmaa</td>
<td>14.9</td>
<td>0.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Pohjois-Karjala</td>
<td>7.2</td>
<td>0.3</td>
<td>6.9</td>
</tr>
<tr>
<td>Pohjois-Pohjanmaa</td>
<td>15.7</td>
<td>0.6</td>
<td>15.1</td>
</tr>
<tr>
<td>Pohjois-Savo</td>
<td>24.0</td>
<td>0.5</td>
<td>23.5</td>
</tr>
<tr>
<td>Päijät-Häme</td>
<td>10.9</td>
<td>0.6</td>
<td>10.3</td>
</tr>
<tr>
<td>Uusimaa</td>
<td>29.0</td>
<td>3.9</td>
<td>25.1</td>
</tr>
<tr>
<td>Varsinais-Suomi</td>
<td>7.4</td>
<td>1.1</td>
<td>6.3</td>
</tr>
<tr>
<td><strong>Whole country</strong></td>
<td><strong>226</strong></td>
<td><strong>12</strong></td>
<td><strong>214</strong></td>
</tr>
</tbody>
</table>
6.1.2. Evaluation of the value of weather services

The concept of the weather service value chain was introduced in chapter 3 and 4. The potential value of weather information service is filtered through seven steps. In chapter 4.2 we estimated the approximate magnitudes of each of these steps by literature review. Some of these steps entail more uncertainty or could be more controversial than others. More study is needed – especially in 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. 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. This is shown in figure 6.1.

![Figure 6.1 Weather service value chain and filters](image)

Since we know that the current average value of road accidents is 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

\[ = X - 0.14X, \text{where } X \text{ is the estimate of accident costs without any weather information, } X \]

\[ = 262 \text{ million euros} \]

By manipulating the steps, we notice that with a 100% accurate forecast (leaving other factors untouched) the value of weather forecasts would be 39 million euros, which is 3 million higher than with the current 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.

### 6.1.3. Estimates of benefits for Europe as a whole

Palma and Rochat (2000) studied the travel decisions made by vehicle drivers in Geneva with respect to weather information. A similar survey has also been made in Brussels (De Palma et al. 1997). 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 (Sihvola et al. 2008, Sihvola and Rämä 2008) 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 a European level. Although there might be some cultural differences, we believe that the weather service value chain introduced in chapter 4.2 is 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 (see Bläsche et al 2011). With these assumptions the total welfare lost from road accidents in Europe would amount to 20.7 billion Euros as indicated in the EWENT WP4 reports (Bläsche et al 2011; Nokkala et al 2012). Without any weather information, we estimate that the 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 would 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

\[ = X - 0.14X, \text{where } X \text{ is the estimate of accident costs without any weather information, } X \]

\[ = 24,098,822,000 \text{ euros} \]
6.2. **Case study 2, an interview with the operative managers of The Finnish Transport Agency**

The Finnish Transport Agency is responsible for the management, development and maintenance of the Finnish railway network. The goal is to keep the current railway network in such a condition that traffic and safety needs are met and an effective transit capacity is guaranteed (Finnish Transport Agency). Operative managers make all the real-time decisions about scheduling and routing trains. They also give warnings about extreme conditions to the traffic operator (VR) and maintenance operators.

Currently operative managers stated that they use mainly public weather information which they acquire from television, radio and internet. If they notice something extreme about future conditions they contact a meteorologist on duty and ask for more specific forecasts. Initial decision whether to acquire more information or not, and thus how to interpret future weather conditions and forecasts is usually made by the operative managers. In addition to public weather information, they have bought a real-time lightning data base from the Finnish Meteorological Institute (FMI). Official warnings on extreme weather (by FMI) are by default delivered also to the Finnish Transport Agency.

The weather conditions which operative managers found most harmful are heavy snowfall (especially combined with high winds and low temperatures causing malfunctions in switches), lightning (electricity problems), storms and heavy winds (trees fall on rails), extreme temperatures (icing of switches or melting/bending of rails), heavy rains and flooding (water on rails). No monetary value for the losses caused by weather extremes has yet been estimated.

The most essential weather information for the operative managers are snow and storm warnings. During the snowfall it would also be highly beneficial to know the wind direction and temperature levels. At the moment no automatic snow fall warnings are issued and operative managers have to sort out the information from the public weather information. Also requested was information about floods and sea/lake water levels near rail tracks. Even the current level of weather information is highly beneficial for Transport agency in securing the current level of service.

Still there is a very high potential for improvements. Most essential weather information in winter time is the forecasted rate of snowing. Snow-removal contractors need the snow warning 12 hours before the actual snow event from the operative managers. It is the responsibility of the operative managers to give the warning. A snow warning is given when the expected snowing rate is 5-10 centimetres in 12 hours. The contractor then raises its service level as much as needed to secure the scheduled traffic. A snow alarm is a message for more severe snow conditions and a snow-removal contractor needs the alarm 48 hours before the actual event or they are not held.
responsible for not being able to perform their duties. Snow alarm is given when snowing rate is more than 10 centimetres in 12 hours, temperature is below 5 Celsius degrees and winds are higher than 5 m/s (directive values and not all of them need to come true). For the winter traffic to perform properly it is of high importance to keep the rails and more specially the switches clear from heavy snow. The requested lead-times are 12 hours for heavy snowing (5-10cm in 12 hours) and 48 hours for blizzards (10cm or more in 12 hours).

Due to the fact that the snow information is very important and information gathering is performed mainly by operative managers (not meteorologists) from public information, it is easy to conclude that a better service could be provided which has a potential to be highly beneficial. Even a simple warning of future snow events by a meteorologist (by e-mail or phone call) to the person in charge of operations would create value. More sophisticated communication systems could be even more beneficial. The transport agency reported that they are even willing to pay for these services.

When evaluating the steps of the weather service value chain, it must be noted that the operative managers have more weather information at hand. A set of services has been sold to the Transport Agency and they are available through the website of FMI. Some of this information is clearly still too complex to grasp easily and even harder to use appropriately for the operative decision-makers. Education about interpreting weather forecasts and nowcasts is recommended. Automatic warnings about most harmful conditions would also help the operative managers to realize that extreme weather is to be expected. Giving numerical values for the different steps in the weather value chain is hard, but best “guesses” are provided to give some light for the magnitude of how beneficial improving these steps could be:

1) **the extent to which weather forecast information is accurate** – longer lead times and better spatial accuracy requested – 80%

2) **the extent to which weather forecast information contains appropriate data for a potential user** – some more data needed (sea levels etc.), but mainly the data requested would have been available via the FMI websites – 85%

3) **the extent to which a decision maker has (timely) access to weather forecast information** – internet is the main source for the operators and weather information is constantly updated in the FMI websites, expert opinions (when needed) from meteorologists are sometimes hard to get (meteorologist is occupied) – 95%

4) **the extent to which a decision maker adequately understands weather forecast information** – very low utilization for the current information, easier-to-grasp information and education needed, - 35%

5) **the extent to which a decision maker can use weather forecast information to effectively adapt behaviour** – if weather information is correctly understood, operative managers have good professional skills to effectively use it (delay some trains, send snow patrols to remove snow, warn passengers), steps 5-6 combined 95%

6) **the extent to which recommended responses actually help** to avoid damage due to unfavourable weather information – see step 5
As shown in the figure below, each step reduces the value of weather information for the end-user. If these estimates turn out to be correct, only about 20% of the potential value of weather information is actually perceived. Huge potential for improvement exists mainly by finding ways to communicate the information more effectively. This potential can only be created with cooperation between the meteorological institute and the end-user, because education about the right interpretation of forecast is also essential. Figure 6.2 shows how the potential value is reduced step by step. Blue bar represents each filter and red bar shows the cumulative amount of value left after each step.

**Figure 6.2 Weather service value chain for rail transport**

6.2.1. **An example from the year 2010-2011 in Finland**

In 2010, the main reason for delays in rail transport was weather (VR). In the calculations we use the value of 50% of all delays to keep the estimates as conservative as possible. During the winter months snow and very low temperatures caused problems. During the spring delays were caused by frost damages and during the summer by thunderstorms. Of the long-haul trains, 75.8% arrived on time (not later than 5 minutes beyond the scheduled arrival). 88% of the delays were 15 minutes or less (average of 10 minutes) and 12% over 15 minutes (VR). About 14 million trips are made annually with long-haul trains (YLE). The value of time in long-haul bus trips is 8 euros according to Finnish Transport Agency and we use this rating in this calculation of rail transport delay costs.

$$Weather \text{ related delay costs on long – haul trips}$$

$$= 0.5 \times 0.242 \times 0.088 \times 0.17h \times 8 \text{ euros per hour} + 14000000 \times 0.242 \times 0.12 \times 0.25h \times 8 \text{ euros per hour} = 2.4 \text{ million euros}$$

Of the short-haul trains 88.5% were punctual (arrival not later than 5 minutes of the scheduled arrival) and 11.5% were late. 56 million trips were made with short-haul trains in 2010. Most of these were trips to work (VR) when the value of time is estimated to be 10 euros/hour (Road transport management) which we use in this calculation.
Weather related delay costs on short – haul trips

\[ = 0.5 \times 56\,000\,000 \times 0.115 \times 0.1 \text{ hours} \times 10\text{ euros per hour} = 3.2\text{ million euros} \]

As these estimates are very conservative (some other studies have been made with the value of time of 43 euros per hour), the value of weather related delay cost for passengers in 2010 were at least 5.6 million euros. We estimate that without any weather information the delay costs would be around 7 million euros and the value of current weather information to be about 1.4 million euros. By setting the step 1 to 100 % accurate forecast, we notice that the benefits would increase by about 0.5 million euros in the form of reduced delays.

Delay costs with the current weather information

\[ = X - 0.20X, \text{where } X \text{ is the estimate of the delay costs without any weather information}, X \]

\[ = 7\text{ million euros} \]

Accident costs without weather information

- Accident costs with current level of weather information

\[ = \text{The value of weather information} = 1.4\text{ million euros} \]

When these results for rail transport are compared to the results for road weather information, we notice that the value is about 3.9 % of the value for the vehicle drivers (1.4 million euros/36 million euros). While the majority of train delays in Finland are due to bad weather, a lower share of delays can be explained by adverse weather in many other countries in Europe. Thornes and Davis (2002) for example estimated that only 20 % of delays were weather related in the United Kingdom. In this case, the value of weather information would only be about 1.6 % of the value for the vehicle drivers (\( \frac{1.4\text{ million euros} \times (0.2)}{36\text{ million euros}} = 0.01555 \ldots \)). By using these lower (1.6%) and higher (3.9%) fractions the lower estimate of the total benefits of weather information for the railway users in Europe would amount to 54 million euros and the higher estimate to 132 million euros. These estimates are based on several assumptions and simplifications, but give an indication of the order of magnitude of the forecast value for the railway sector in the form of reduced delay costs for the users.

6.3. Case study, combining data from literature review and statistics to estimate the value of more accurate forecasts in aviation

For estimating the incremental value of better weather information on aviation we rely on Eurocontrol statistics (Eurocontrol PRR 2006-2010). A yearly report called “Performance Review Report” includes key figures and information about many aspects of air traffic performance and air traffic management. Since 2006 the costs of weather related delays have been estimated. These estimates are shown in table 6.4. However, these cost estimates do not include the costs of
cancelled flights or the costs of additional time spent in the air in holding patterns. In this chapter, we try to include costs of weather related cancellations into the figures which still remain conservative estimates of the total weather related costs. An average unit-cost of airplane use of 81 euros per minute is assumed (PRR_2010).

Table 6.4 Weather related delay costs (million Euros), 2006-2010 (Eurocontrol PRR 2006-2010)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total delay due to</td>
<td>5.0 M</td>
<td>5.5 M</td>
<td>5.4 M</td>
<td>4.0 M</td>
<td>5.6 M</td>
</tr>
<tr>
<td>weather in minutes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated costs of</td>
<td>€ 406 M</td>
<td>€ 442 M</td>
<td>€ 436 M</td>
<td>€ 326 M</td>
<td>€ 453 M</td>
</tr>
<tr>
<td>weather related</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>delay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PRR_2010 is the first report that has systematic data about flight cancellations. PRR_2008 mentions that 1.1% of the short-haul and 0.4% of the medium and long-haul flights were cancelled in the summer 2008. These cancellations may have happened due to several reasons. In 2008, the number of cancellations had not been collected consistently over Europe. 2009 report does not include an estimate of the flight cancellations at all (PRR_2009).

The 2010 PRR reported approximately 111 000 cancellations as a result of the volcanic ash cloud in April/May 2010 and that some 45 000 flight were cancelled due to bad weather conditions in 2010. The cancellation costs as a result of the volcanic ash cloud are not included in the following calculations. As no data are available about the cancellations due to adverse weather from any other year but 2010, we estimate the number of cancellations with the ratio of adverse delay minutes and flight cancellations of 2010. This means assuming a direct relationship between weather related delay minutes and cancellations which might be a strong assumption.

The cost of a flight cancellation is highly dependent on factors such as aircraft size and load factor. Some rough estimates on the costs of cancellations have been calculated. These can be found from the report: “Standard inputs for Eurocontrol cost benefit analyses”.

Valuation study 1: (SESAR evaluation team for Eurocontrol, PRR_2009)

Typical values are:

- 50 seat narrow body aircraft – 3400 €
- 120 seat narrow body aircraft – 16000€
- 400 seat wide body aircraft – 75000€

Valuation study 2: (EGNOS Multi-Modal costs and benefits)

- average cancellation cost of 7000€ (adjusted from 1999 prices)

We use the average cancellation cost of 7000€ in this study, since the distribution of flight cancellations per aircraft is unknown. The results are presented in table 6.5.
Table 6.5 Cancellations and weather related costs (modified Eurocontrol PRR 2006-2010)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>The number of</td>
<td>32000</td>
<td>44000</td>
<td>43000</td>
<td>32000</td>
<td>45000</td>
</tr>
<tr>
<td>cancellations (estimate)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weather related</td>
<td>€ 686 M</td>
<td>€ 750 M</td>
<td>€ 737 M</td>
<td>€ 550M</td>
<td>€ 768 M</td>
</tr>
<tr>
<td>costs per year (delays + cancellations)</td>
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On average, the costs have been close to 700 million euros a year. The yearly variations can be mostly explained by inter-annual variations in the extent of adverse weather conditions, as the traffic has not increased significantly since 2006. Despite a moderate recovery of +0.8% in 2010, overall traffic still remains below 2007 levels (PRR_2010).

Avoidable costs

The previously used weather service value chain model (described in chapter 3.3, applied in 6.1 & 6.2) is not applicable in estimating the value of weather forecast for aviation. First, modern aviation could not exist at all without weather information. There is no point in estimating the value of the current level of aviation weather information as whole. Second, aviation is a very professional user of meteorological information. The use of information is strictly regulated and there is little room for improvements in other steps in the weather service chain except the first step concerning weather forecast accuracy (step 1 in the model). Improvements in forecasts as better accuracy and decreased variation in accuracy however would be likely to have a strong impact on the efficiency of aviation (McRea et al. 2007; Klein et al. 2009). For example, if the uncertainty about the weather could be removed, planes would not have to carry as much fuel as they carry as with the current weather information. When the forecast of good weather is known with certainty, the fuel load can be reduced to a minimum level. There would still be some uncertainty about the landing time and place because of other factors such as traffic congestion, but the extra fuel load would decrease in absence of the weather uncertainty. Also scheduling and route choices could be optimized on a tactical level (Sarpila 2008). On a strategic level, this could mean a different kind of system of route planning and scheduling (McCrea et al. 2007).

A study by Klein et al. (2009) had the objective to estimate avoidable delays and costs that can be attributed to terminal weather forecast inaccuracy. They estimated the avoidable portion of arrival delays and cancellations due to terminal weather forecast inaccuracy. The avoidable portion of arrival delays due to terminal weather improvements is about 40 % of total delays. They do not present any number for the avoidable cancellations. If 40 % is applied in the total weather related costs in Europe, costs of 280 million Euros a year could be avoided in the forms of reduced delays and cancellations. Avoidable costs per weather phenomenon are presented in figure 6.3.
The estimate of 280 million euros of avoidable costs does not include other benefits, such as better fuel-efficiency due to reduced fuel-load, better route-choices or the reduced costs of time and fuel spent in the air in holding patterns. Improvements in forecast accuracy could lead to an alternative system of scheduling and route planning as presented in McCrea et al. (2007). This could eventually lead to additional benefits. The magnitude of potential extra value is likely to be higher than 280 million euros. Further research in this area is needed to give reliable estimates.
7. Conclusions

Adverse weather conditions can raise transport costs directly due to higher operational cost (e.g. fuel use, road clearance), higher time cost (delays and cancellations) and higher accident risks. Weather can have indirect effects on a transport mode as well, when weather affects the capacity or demand of other transportation modes and consequently a part of the users decides to switch transport mode. Weather information enables better decisions by the various decision makers, i.e. travellers, transport service operators, and infrastructure owners. The resulting better preparedness and better informed decisions attenuate extreme weather induced cost and price effects, which is in principle a common benefit for all market parties. In this respect it merits to emphasize that adequate weather and climate information affects short term (operational) decision making in transport (reducing acute risks), as well as long term (strategic) decision making on investments and maintenance cycles (improving the system’s coping range).

It has been shown in this report that there are quite marked differences in the forecasting capability of different weather variables and phenomena. However, looking at past historical forecast performance, there is a definite positive trend in the forecasting capabilities. The improvement in forecast quality exhibits a more or less steady increase in the number of projected days of one day per decade. Therefore, it is realistic to believe a similar trend will continue and to expect the usefulness of final weather forecasts to evolve by one day per decade until the foreseeable future. This fact can be utilized to support weather critical decision making and value assessments of weather services.

Further improvement of the accuracy of weather information may be expected to reduce the costs of adverse weather conditions even more. The effectiveness of the improved accuracy varies nevertheless between transport modes. The more professional the user is in terms of meteorological information processing, the larger the larger share will be of the maximum benefit potential that is realized. Improvements of information include, but are not limited to, increased accuracy of weather forecasts. More benefits are realized by means of more efficient communication and by increased ability of the decision makers to use weather information.

Attribution of cost reductions related to coping with adverse weather conditions in transport to particular improvements in weather services is in most cases – in principle – possible. However, one should allow for – sometimes considerable – uncertainty ranges in estimated benefits. The apparent coping range often also changes due to other developments in technology, traffic regulation, changes in habits and norms, evolution in forecast skill distributions, etc.

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
No single methodology could handle the estimation of the benefits for all different transportation sectors or modes. The selection of methods depends on the available data and the transport mode in question. Each transport sector and mode uses meteorological information in different ways and for answering different questions.

The significance of differences in ability to communicate and use the weather information can be illustrated by means of weather service chain analysis (WSCA). WCSA considers seven filters which forecast services are passing through the entire chain from 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 realize. The stages are:

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

Without meteorological services there could not be any commercial aviation at the scale as we know it nowadays. For this reason there is no point in calculating the total value of weather information for the industry. On the other hand an incremental improvement of the current aviation weather service level can be assessed. With more accurate forecasts costs of unnecessary precautionary measures and weather related delays and cancellations could be avoided. Another important feature to consider is the knock-on effect in a complex network of flights. One delay can potentially create a multiple number of subsequent delays. The benefits of avoiding one (initial) delay are then larger than the direct costs of that particular (initial) delay. For civil aviation in Europe it is estimated that about 280 million Euros per year could be saved in case of (almost) ideal weather services in relation to air terminal weather forecast inaccuracy. The estimate includes only the benefits of avoided delays and cancellations.

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 resulting from 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.

One of the least studied sectors with respect to weather information utilisation is rail transport. To enable the project researchers to use WSCA an interview with the operative managers of the Finnish transport agency (section rail network maintenance) was conducted. The bottleneck turned out to be step 4 of the WSCA as the decision makers did not adequately understand crucial parts of the weather forecast information. As a consequence the level of utilisation of weather information remains low and thereby leads easily to delays in train services under adverse weather conditions. Delays are a considerable burden for train service users, because lack of competition and alternatives may prevent them from switching to another operator or to another mode. The current value of weather information for rail road users is about 1.4 million euros in travel time savings. For European travellers as a whole the benefits are loosely estimated at somewhere between 50 million and 130 million euros per year.

Another often ignored transport mode is non-motorised traffic (pedestrians and bikers). The costs of tripping and slipping are truly substantial, especially in Nordic countries. For example, the estimate for Finland is 2.4 billion euro per year (including cost of temporary and permanently lost working hours). Tailored weather information has the potential to be highly beneficial in the reduction of these costs. Part of the benefits are realized through better service level in maintenance and part from more informed decisions of pedestrian and cyclists. These decisions include the right choice of footwear or tires for the cyclists, timing of the trip, route choice, mode choice and time of departure.
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Annex A – Alternative formulations of utility and demand functions

**Cobb-Douglas**

We suppose for an example that the utility function is of the often used Cobb-Douglas form \( u(x_1, x_2) = x_1^a x_2^b \), which can be rewritten to \( \ln u(x_1, x_2) = a \ln x_1 + b \ln x_2 \). The problem consumer wants to solve is to maximize above utility function with such a way that the budget constraint is \( p_1 x_1 + p_2 x_2 = y \).

The basic way to solve maximization problems with a constraint in economics is to use the Lagrange’s method (Varian 2009). We set up the Lagrangian:

\[
L = a \ln x_1 + b \ln x_2 - \lambda (p_1 x_1 + p_2 x_2 - y)
\]

and get the first order conditions

\[
\frac{a}{x_1} - \lambda p_1 = 0, \quad \frac{b}{x_2} - \lambda p_2 = 0 \quad \text{and} \quad p_1 x_1 + p_2 x_2 - y = 0,
\]

with three equations and three unknowns we just need to solve the equations. After a little calculus we get demand functions for the two goods,

\[
x_1 = \frac{a}{a+b} \frac{y}{p_1} \quad \text{and} \quad x_2 = \frac{b}{a+b} \frac{y}{p_2}.
\]

If \( y \) is defined as the net disposable income after saving, it would equal the total budget meant to be used in the considered period. \( y \) can in that case be rewritten as \( \sum_i p_i x_i \), which allows for explicit introduction of cross-price effects in the demand function of any of the distinguished goods. By taking the logarithm at both sides a system is obtained which is linear in the parameters and hence straightforward to estimate.

This is an illustration how demand is derived from the optimal choices of utility functions. The exponent in the Cobb-Douglas utility functions depend on the preferences of consumers and represent the fractions of income consumer spends on each good. Hence, the demand function is often written as

\[ u(x_1, x_2) = x_1^a x_2^{1-a}. \]

As the preferences change, so does the fraction of income spent on each good. (Varian 1999).

**Stone-Geary (linear expenditure system)**

The linear expenditure system of Stone-Geary builds on a similar utility function as indicated above, but is more generalised assuming \( n \) different expenditure categories, while enabling the notion for minimum consumption requirements (\( \gamma_i \)) for all or some categories \( i \) (if all \( \gamma_i = 0 \) the system would collapse to the above referred Cobb-Douglas utility function).
As in the example in the previous section, by taking the logarithms the system can be linearized. For the demand of each expenditure category \( i \) is than expressed as follows:

\[
x_i = \gamma_i + \frac{\beta_i}{p_i} \left( Y - \sum_j y_{j \cdot p_j} \right)
\]

where \( p_i \) denotes the price of the bundle of goods related to expenditure category \( i \) and \( Y \) the disposable income level.

**Almost Ideal Demand System (AIDS)**

Many empirically estimated expenditure systems are based on the so-called Almost Ideal Demand System developed by Deaton and Muellbauer. It is usually expressed in terms of the budget share of an expenditure category (for a particular type of household). In the version below also household characteristics (such as age of the main earner; number of household members, education level) have been included.

\[
w_i = \alpha_i + \beta_i \ln(Y_i) + \sum_k \{ \varphi_{ki} \ln(hh_k) \} + \sum_i \{ \varphi_i \ln(p_i) \}
\]