Winter Problems on Mountain Passes

- Implications for Cost-Benefit Analysis

Abstract

Cost-benefit analysis is a tool in government decision-making for determining the consequences of alternative uses of society's scarce resources. Such a systematic process of comparing benefits and costs was adopted in early years for transportation projects and it has been the subject of much refining over the years. There are still some flaws, however, in the application of the method. In this article we have studied the impact of weather conditions on traffic speed on low traffic roads often exposed to adverse weather. This is an issue not currently considered in the cost-benefit analysis of road projects. By using two analytical approaches—structural equation modelling and classification and regression tree analysis—the impact of the weather indicators temperature, wind speed, and precipitation on traffic speed has been quantified. The data relates to three winter months on the European Route 6 road over the mountain pass Saltfjellet in Norway. Increase in wind speed, increase in precipitation and temperatures around freezing point all caused significant decrease in traffic speed in the case studied. If actions were taken to reduce the impact of adverse weather on traffic (e.g. by building a tunnel through the mountain) this study indicates that the road users would gain a total benefit of approximately 2,348,000 NOK (282,000 EUR) each winter at Saltfjellet if all the weather related benefits were included. We argue that this is a significant number that is highly relevant to include in CBAs. This applies both to the CBAs of new transportation projects as well as when resources are allocated for operation, maintenance, and monitoring of the existing transport systems. Including the weather related benefits would improve the application of CBA as a decision-making tool for policy makers.

1. Introduction

Mountain passes are often exposed to rough weather, especially during the winter. The Norwegian Public Roads Administration (NPRA) has identified strong wind, snow and driving conditions around freezing point as problematic for traffic on mountain passes (NPRA, 2012). The importance of these weather variables for traffic is supported by previous research on this topic (see e.g. Agarwal, Maze, & Souleyrette, 2005; Al Hassan & Barker, 1999; Cools, Moons, & Wets, 2010; Nosal & Miranda-Moreno, 2014). Adverse weather[1] may impact driving conditions on mountain pass roads in several ways. First, the combination of wind and snow causes snowdrifts either because the wind moves snow already lying on the ground, or because there is wind and snowfall at the same time. Snowdrifts reduce visibility and block the roads (NPRA, 2012). Second, the wind speed is sometimes so great that there is a risk of vehicles being blown off the road. Finally, driving conditions around freezing point cause the roads to be slippery and the risk of accidents increases. It is challenging and costly to operate mountain passes during the winter because of the problems created by adverse weather. Sometimes the operating crews have to close the roads or traffic is led in convoys because it is not safe to allow the free flow of traffic (NPRA, 2012).

It is not only the operation of mountain passes that is costly; road users also experience increased travel costs because of problematic traffic conditions in adverse weather on mountain passes. There are costs related to delays and unreliable travel times, increased risk of accidents, and extra material costs due to the use of spiked tires and chains (Hagen & Engebretsen, 1999). Much research has been conducted addressing the problems with delays and unreliable travel times caused by adverse weather, and the conclusions are that these problems can be extensive and that people are willing to pay to avoid them (see e.g. Bates, Polak, Jones, & Cook, 2001; de Jong, Kouwenhoven, Kroes, Rietveld, & Warffemius, 2009; Li, Hensher, & Rose, 2010; Sikka & Hanley, 2013; Tseng & Verhoef, 2008). The extensiveness of the problem can be illustrated by the Oak Ridge National Laboratory study, which estimated the delay experienced by American drivers due to adverse weather conditions in 1999 to be 46 million hours (cited in Rakha et al., 2007).

All road projects in Norway are subject to cost-benefit analysis (CBA). The Norwegian Public Roads Administration (NPRA) states that the aim of the CBA is to systematically consider all relevant benefits and costs that a road project will impose on society (NPRA, 2006). Yet despite the harsh climate and the fact that many important road sections are exposed to adverse weather, adverse weather impact on traffic is not considered in CBAs of road projects. As mentioned above, research reveals that people

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[1] In this context, adverse weather is defined as "atmospheric conditions at a specific time and place that are unfavourable to optimal traffic conditions" (El Faouzi, Billot, Nurmi, & Nowotny, 2010).

are willing to pay for both travel time savings and reliable travel times (see e.g. Asensio & Matas, 2008; Bates et al., 2001; Carrion & Levinson, 2012; de Jong et al., 2009; Li et al., 2010; Sikka & Hanley, 2013). Travel time savings typically produce 60 percent of the traditionally quantified user benefits in the CBA of new road projects (Hensher, 2001). However, travel time savings related to the avoidance of delays and uncertainty caused by adverse weather is not included, and the value of increasing the reliability of travel times is often not included at all. In a recent study, Peer, Koopmans and Verhoef (2012) show how travel time variability can be predicted for use in CBAs. They point out that in order to be able to include in CBAs the benefits associated with measures increasing travel time reliability, it is necessary both to know the extent of unreliability in the transport system today and the driver's valuation of unreliable travel times. This also applies to delays.

Thorough work has been done to put monetary values on travel time savings (NPRA, 2006), but to what extent adverse weather causes delays and unreliability at mountain passes is poorly covered. This makes it impossible to include these effects in CBAs, which again means that the net benefits of projects aimed at reducing the problems are valued too low, and projects may lose priority to other projects with higher net benefits. The building of a tunnel through a mountain in order to avoid a challenging mountain pass is an example of a project which would reduce the impact of adverse weather on traffic and hence result in both travel time savings and higher travel time reliability. Improvement of the road structure (location in the terrain, road width, curvature etc.) is another example. Hagen & Engebretsen (1999) conducted a supplementary CBA of two tunnel projects located in the county of Nordland, Norway, and estimated an increase in cost-benefit ratio from 0.42 to approximately 0.90 when the weather-related benefits of travel time savings, increase in travel time reliability and reduction in material costs were included. The results were based on a stated preference study among the users of the road.

Maze, Agarwal & Burchett (2006) have identified three predominant and measurable dimensions of the weather's impact on traffic: traffic demand, traffic safety, and traffic flow relationships. Research has focused on all three dimensions for quite a while, and the interest for the topic has increased lately in the light of the growing awareness of climate change impact on the transport system (see e.g.,Arana, Cabezudo, & Peñalba, 2014; Böcker, Dijst, & Prillwitz, 2013; E. Hooper, Chapman, & Quinn, 2013; Khaleghei Ghosheh Balagh, Naderkhani, & Makis, 2014; Asad J. Khattak & De Palma, 1997; Asad J Khattak, Kantor, & Council, 1998; Lam, Shao, & Sumalee, 2008).

The aim of this study has been twofold. First, two analytical approaches—structural equation modelling (SEM) and classification and regression tree (CART) analysis—have been applied in order to be able to quantify how weather influences traffic flow (here represented by traffic speed) on

mountain passes. Second, the results from the analysis have been used to quantify the economic consequences of the impact of adverse weather on traffic flow.

The use of speed as an endogenous variable in the analysis is supported by Koetse and Rietveld (2009), who identified speed choice as one of several possible behavioural reactions to adverse weather (for further details on behavioural reactions in transport, see de Dios Ortúzar and Willumsen (2011)). Difficult driving conditions caused by adverse weather represent only one factor determining speed choice. The literature has identified several other factors determining speed choice:

- speed limit, cost of fines, and the risk of being caught driving too fast (Rietveld & Shefer, 1998);
- individual characteristics of the driver, such as age, gender, and income (Rietveld & Shefer, 1998);
- information about the transport system and previously acquired knowledge and experience (Dia, 2002);
- perception of driving conditions and risk (Dia, 2002; Fuller, 2005);
- frequency and severity of accidents, characteristics of the road and type of vehicle (De Luca, Lamberti, & Dell'Acqua, 2012; Liu, 2007);
- costs of arriving late (Rietveld & Shefer, 1998).

Keeping task difficulty within selected boundaries has been suggested as a key sub-goal in speed choice (Fuller, 2005). Different levels of task difficulty are thought to be produced in the dynamic interaction between the determinants of task demand and driver capability (Fuller, 2005). Hence, in adverse weather drivers reduce vehicle speed to varying extents.

The context of our study has been the European Route 6 road over the mountain pass Saltfjellet in Norway. Much of the research has been conducted to reveal the impact of weather on traffic, but a common feature of previous literature is the focus on studies in densely populated areas where congestion and road capacity is an issue. Little research has been conducted to quantify the influence of weather on traffic in rural areas (Böcker et al., 2013). One important characteristic of rural environments, which distinguishes them from densely populated areas, is the lack of or limited access to alternative routes (Laird & Mackie, 2009). Reliability of the transport system, for example, may have a large impact on scheduling costs and broader economic benefits in rural areas (Laird & Mackie, 2009). Interruptions in the transport system may impact competition in both the product and service markets as well as the labour market (Laird & Mackie, 2009). The drawback of closed roads during the winter in Norway has been identified by Meersman and Van De Voorde (2001) as a barrier to interconnectivity in European transport.

Böcker et al.'s (2013) review of existing literature on the topic of interest also found the variance in climate regimes covered by the reviewed studies to be limited. Almost all of the studies were located in North-West Europe, North America and Australia. According to the authors, polar climate regions are virtually uncovered. All mountain passes in Norway are defined as polar climate regions according to the Köppen-Geiger classification (cited in Böcker et al. (2013)).

The article is structured as follows: the case, traffic data, and weather data, are described in Chapter 2. Chapter 3 presents the two analytical approaches for determining the impact of weather conditions on traffic speed—structural equation modelling (SEM) and classification and regression tree (CART). In Chapter 4, the results from the SEM and the CART analyses are presented and discussed, while a calculation of benefits related to reducing winter problems on the mountain pass in question is presented in Chapter 5. Finally, some concluding remarks are made in Chapter 6.

2. Saltfjellet
2.1 Case description

The empirical data is collected from the mountain pass Saltfjellet in Norway (see Figure 1). EV6, the main transport corridor from the southern regions to the northern regions of Norway, runs across this mountain pass, which is located at the Arctic Circle and is often exposed to harsh weather conditions. There are two alternative routes for road transport. One of these runs through Sweden and implies increased transport distance. The other, along the coast of Nordland, is characterised by poor road quality and several ferries. In this study, we have chosen Saltfjellet as our case, but there are several other mountain passes in the northern parts of Europe, both further north and south, that are exposed to the same type of winter problems as Saltfjellet.
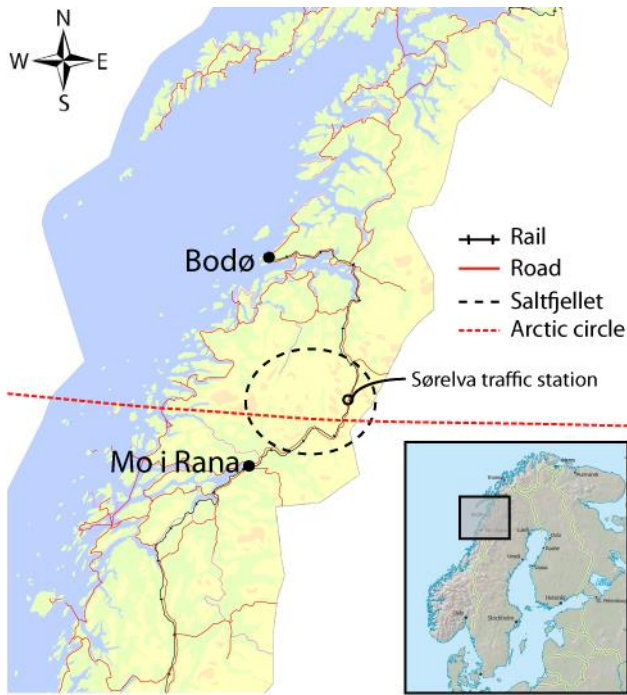
Figure 1: The Saltfjellet mountain region, Norway.

Weather-related traffic problems on Saltfjellet are particularly prominent during the winter season. During this time of year, drivers can expect roads to be covered with snow and ice.[2] The data in this study relates to the time period traditionally classified as winter, which ranges from December 1 to February 29. The data relates to the 2011–2012 winter season, with additional statistics on traffic for the whole year of 2012 (NPRA, 2013b).

Table 1 presents some descriptive statistics of the traffic on Saltfjellet (the data relates to traffic in both the northbound and southbound direction). The traffic density on Saltfjellet varies widely throughout the year with the highest traffic density in July and the lowest in January. Due to adverse weather, the number of days with closures and convoys in the studied period (December 2011– February 2012) was 9 and 18, respectively.

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[2] In northern parts of Norway, car drivers are allowed to use winter tires with spikes from October 16 to May 1 (Lovdata, 2014).

Table 1: Descriptive statistics of the traffic at Saltfjellet (NPRA, 2013b)

Traffic statistics	
Average total daily traffic, 2012	934 vehicles
Average daily traffic July, 2012	2289 vehicles
Average daily traffic, summer 2012 (Jun, July, Aug)	1797 vehicles
Average daily traffic, January 2012	433 vehicles
Average daily traffic, winter 2012 (Dec 2011, Jan and Feb 2012)	459 vehicles
Average proportion of heavy vehicles in 2012 (vehicles ≥ 5.6 m)	28.6%
Average proportion of heavy vehicles, winter 2012 (Dec 2011–Feb 2012)	40.0 %
Days with closures December 2011–February 2012	9 days
Days with convoys December 2011–February 2012	18 days

2.2 Data collection

The empirical data relies on two sources. Data on traffic flow was provided by the Norwegian Public Road Administration (NPRA). The data was collected by an electronic counter (inductive loops in the asphalt covering (NPRA, 2011)) at the traffic station Sørelva on Saltfjellet. This is a measuring point operating at the most detailed level, and traffic volume and speed are measured continuously. The positioning of the electronic counter follows the NPRA's guidelines (2011). The speed limit at this measuring point is 80 km/h; however, 150 metres further south, the speed limit increases to 90 km/h. The data on traffic flow relates to registration of traffic purely in the northbound lane. Because the average speed in the northbound and southbound lanes slightly differs[3], only one lane was chosen for further analysis.

Information on temperatures and wind speeds was obtained from the Norwegian Public Road Administration (NPRA). This data was collected at Sørelva (see Figure 1). Information on precipitation was collected by the Norwegian Meteorological Institute (2014) and are publicly available at the website eklima.no. Precipitation relates to a measuring point located approximately 30 km south of the Sørelva traffic station – on the south side of Saltfjellet. Considering the local variances in precipitation, it is not optimal that the data on precipitation is not collected at the exact same location as the traffic data, but we consider the measuring point to be close enough to produce data with sufficient quality for our study. There were various weather variables available. The decision of which weather variables to include in the analyses was based on previous literature's identification of

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[3] The northbound lane has a somewhat higher average speed than traffic going in the southbound direction because traffic in the northbound direction comes from a zone with a speed limit of 90 km/h and the road has a slight downward slope, whereas traffic in the southbound direction comes from a zone with a speed limit of 80 km/h and travelling vehicles have just passed a curved and upward sloping road section.

important weather variables influencing traffic (see e.g. Agarwal et al., 2005; Al Hassan & Barker, 1999; Cools et al., 2010; NPRA, 2012).

2.3 Data characteristics

The time period studied (1 Dec 2011–29 Feb 2012) included 91 days, providing a total of 2184 possible observations. Due to missing data and some observations being intentionally omitted, the data set contains 1176 observations. Observations were omitted when no vehicles had passed the counter and when the road was closed due to adverse weather conditions. Data examination did not reveal any other patterns in the missing observations.

The weather variables were measured as follows:

- *Air temperature* was measured in degrees Celsius every 10 minutes and averaged for each hour. A bivariate profiling of the relationship between temperature and traffic speed showed a considerably higher variation in traffic speed in the temperature interval [-2, 2] °C, while lower and higher temperatures seemed to have little influence. The descriptive statistics in Table 2 show that maximum temperature in the studied time period was 2.2 °C and the median temperature was -5.0 °C. Most of the time temperatures were either in the interval [-2, 2] °C or below with a minimum temperature measured at -25.9 °C. To our knowledge there exist no literature suggesting that variation in temperatures between -2 and -25.9 °C should influence traffic speed. However, literature has revealed that cold temperature affects traffic demand (see e.g.Cools et al., 2010; Datla & Sharma, 2008). NPRA (2013a) defines driving conditions around freezing point to be in the interval [-2, 2] °C. This temperature interval is associated with slippery roads. A dummy variable, holding the value 1 if the temperature was within the interval [-2, 2] °C, otherwise 0, was introduced to capture this effect.
- *Precipitation* was measured as total millimetres of rain (or snow) each hour. When precipitation appeared in the form of snow, the snow was melted and measured as mm melted snow (Norwegian Meteorological Institute, 2013).
- *Wind* speed was measured in metres per second, 10 metres above ground. Wind speed was recorded every 10 minutes and averaged per hour.

Traffic speed was measured in km/h as an average speed of all vehicles passing the electronic counter each hour. The electronic counter records types of vehicles passing according to their length. In accordance with the NPRA's definition of vehicle classes, private cars and heavy vehicles were defined as vehicles shorter than 5.6 metres and larger than or equal to 5.6 metres, respectively (NPRA, 2013b). The analysis showed no significant difference in the number of vehicles on workdays and weekends,

but the proportion of heavy vehicles was higher on workdays than at the weekends. A continuous variable representing the proportion of heavy vehicles was included to capture this variation in traffic characteristics. Large vehicles hold, on average, a lower speed than private motor vehicles.

According to the guidelines of the NPRA (2012), the following situations call for actions to regulate traffic in adverse weather: snow causing poor visibility and snowdrifts and/or strong wind creating a danger for vehicles to be pushed off the road. There are no exact limits, but traffic is normally led in convoys when visibility is less than 50–100 metres, while it is closed when it drops below 20 metres. For wind speeds above 20 m/s, the guidelines recommend considering closure. When traffic is led in convoy, traffic must follow a leading vehicle (usually a specially designed lorry with a plough), and speed is restricted to a maximum 40 km/h (NPRA, 2012). A dummy variable was used to control for the effect of traffic being led in convoys.

Descriptive statistics and definitions of the variable names are presented in Table 2. All variables are metric except for the variables X_1 and Y_3, which are dummy variables for temperatures around freezing point and convoy, respectively, holding the value 1 if true or 0 if otherwise. Average traffic speed was approximately 78 km/h, which is slightly lower than the speed limit of 80 km/h. The variation in precipitation was characterised by a majority of the 0 value observations and a few large observations. It is worth noting that the average value of precipitation of 0.1 mm/hour translates to 2.4 mm per day. If we consider only the observations with precipitation, then the average value was 0.5 mm/hour. The mean values for traffic speed, wind speed, and proportion of heavy vehicles had only minor deviations from the median value. It is further shown that 59% of the observations had temperatures around freezing point ($X_1 = 1$). Convoy restraint was imposed on approximately 5% of the observations.

Table 2: Descriptive statistics (N=1176)

Variable description	Symbol	Mean	Std. dev.	Min.	Max.	Median
Traffic speed (km/h)	Y_1	78	12	17	130	80
Temperature (°C)		-7.7	5.8	-25.9	2.2	-5.0
Temperatures [-2, 2] °C (yes=1)	X_1	0.59	0.49	0	1	1
Wind speed (m/s)	X_2	5.7	3.6	0.4	19.1	5.3
Precipitation (mm/h)	X_3	0.1	0.4	0	4.5	0
Proportion of heavy vehicles	Y_2	0.40	0.26	0	1	0.37
Traffic led in convoy (yes=1)	Y_3	0.05	0.22	0	1	0

Table 3 shows pair-wise correlations between the variables of interest. All variables were significantly correlated with traffic speed. The magnitude of multicollinearity between the exogenous variables was relatively small and should not interfere with our analysis (Hair, 2010). Table 3: Pair-wise correlations (N=1176)

Variable	Y_1	X_1	X_2	X_3	Y_2	Y_3
Y_1	1					
X_1	-0.24[a]	1				
X_2	-0.37[a]	0.31[a]	1			
X_3	-0.31[a]	0.18[a]	0.24[a]	1		
Y_2	-0.28[a]	0.07[a]	0.08[a]	0.12[a]	1	
Y_3	-0.33[a]	0.17[a]	0.23[a]	0.27[a]	0.05	1

[a] Indicates significance at the 5% level.

3. Analytical Approach

Two different analytical approaches were used in the analysis: Structural equation modelling (SEM) and classification and regression tree (CART) analysis. The two methods are presented in section 3.1 and 3.2, respectively. SEM is a confirmatory method where the specification of structural relationships is guided by theory (Hair, 2010). The CART analysis is to a larger extent a data driven technique because relationships are not specified prior to analysis. However, the choice of which variables to include in the analysis was guided by the same theory as for the SEM analysis. The difference between these methods was exploited to test the validity of the results.

The dataset contains time series data characterised by a temporal ordering of the observations, but because the aim of the analysis was to model the contemporaneous relationship between the weather variables and traffic speed, a "static time series model" was used (Wooldridge, 2013). This is appropriate because when traffic speed is adjusted as a response to adverse weather, this is assumed to be an immediate response unaffected, for example, by yesterday's weather. Hence, autocorrelation should not be a problem.

3.1 Structural Equation Modelling (SEM)

Structural Equation Modelling (SEM) is a powerful technique which can be used to capture causal effects of the exogenous variables on the endogenous variables and causal effects of the endogenous variables on each other (Golob, 2003). The ability of SEM to handle endogenous variables was favourable for this analysis because of the presence of the two endogenous variables Y_2 (proportion of heavy vehicles) and Y_3 (traffic led in convoy). These two variables are influenced by weather conditions while at the same time having direct impact on traffic speed. First, the proportion of heavy vehicles, Y_2, increases in adverse weather because the demand for leisure traffic is more sensitive to adverse weather than the demand for commercial traffic here represented by heavy vehicles. Since

heavy vehicles on average are running at a lower speed, increase in the proportion of heavy vehicles will cause a reduction in average speed. Second, during particularly unfavourable weather conditions, convoy, Y_3, is initiated imposing restriction in speed limit. See further explanation of the endogenous relationships of the variables in section 2.3. The model is assumed to be a recursive path model because all the variables are observed (Kline, 2011). In addition, all causal effects in the model are unidirectional because theoretically there are no reasons to believe that traffic should be able to affect the weather, at least not in the short run. The disturbances are assumed to be uncorrelated. Figure 2 illustrates the model. The model is overidentified with one degree of freedom.
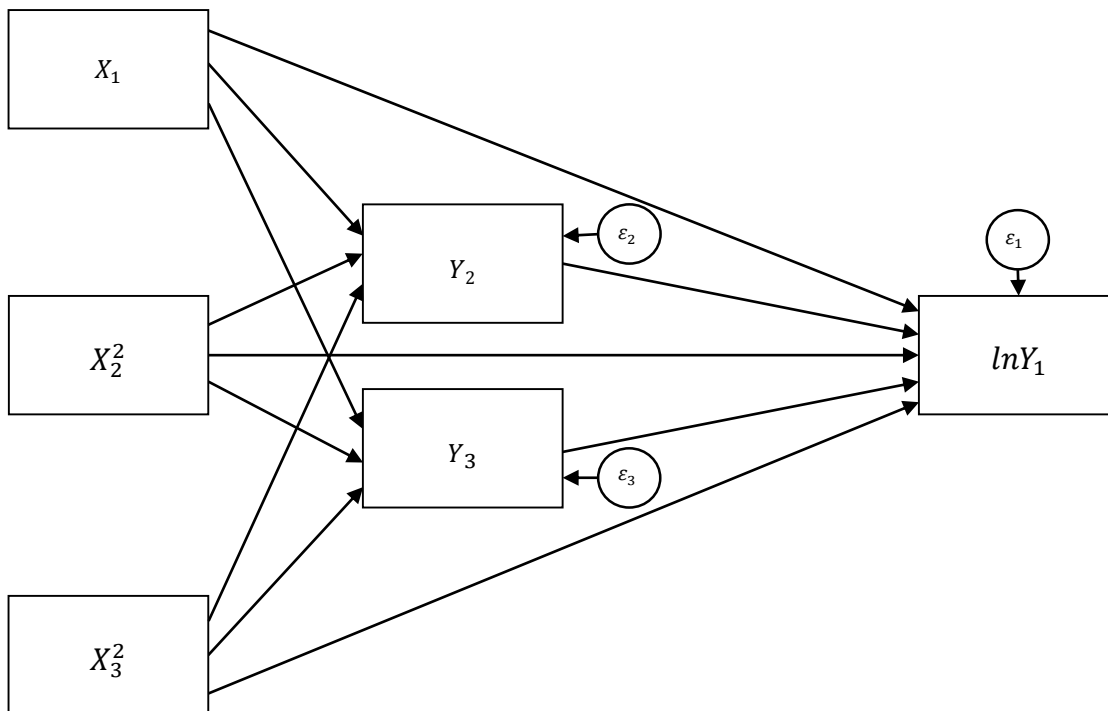

Figure 2: The model. X_1= temperatures around freezing point, X_2= wind speed, X_3= precipitation, Y_2= proportion of heavy vehicles, Y_3= traffic led in convoy, Y_1 = traffic speed, and the corresponding disturbance terms are indicated by epsilon.

The model is composed of three simultaneous equations which are estimated concurrently:

(1) $\qquad Y_1 = e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2{}^2 + \beta_3 X_3{}^2 + \beta_4 Y_2 + \beta_5 Y_3 + \varepsilon_1}$

(2) $\qquad Y_2 = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2{}^2 + \alpha_3 X_3{}^2 + \varepsilon_2$

(3) $\qquad Y_3 = \gamma_0 + \gamma_1 X_1 + \gamma_2 X_2{}^2 + \gamma_3 X_3{}^2 + \varepsilon_3$

In equations (1), (2) and (3) the endogenous variables traffic speed, Y_1, proportion of heavy vehicles, Y_2, and traffic led in convoy, Y_3, are explained by temperatures around freezing point, X_1, wind speed,

X_2, and precipitation, X_3, which are all exogenous variables. See section 2.3 for further explanations of the variables.

For the variables precipitation and wind speed, it is not reasonable to assume a linear relationship on the effect of average traffic speed. This assumption is supported by Böcker et al. (2013), who argue that studies often wrongfully assume linear relationships between weather and travel behaviour. The effect on traffic speed is negligible for low values of precipitation and wind speed. As the weather becomes more adverse, the negative effect increases more than proportionally. To capture the nonlinear relationships the endogenous variable traffic speed is log-transformed and quadratic transformations of the weather variables wind speed and precipitation are used (see equation (1)). Both wind speed and precipitation are assumed to influence traffic speed negatively. It is therefore reasonable that $\beta_2, \beta_3 < 0$ gives negative, first-order derivatives $(\partial Y_1 / \partial X_2, \partial Y_1 / \partial X_3 < 0)$. Because, $\beta_2, \beta_3 < 0$, the values of wind speed and precipitation are non-negative, and traffic speed is log-transformed, the effects of precipitation and wind speed on traffic speed will be s-shaped. The second order derivative for X_2 is $\partial^2 Y_1 / \partial X_2^2 = 2\beta_2 Y_1 (2\beta_2 X_2^2 + 1)$, which changes sign at $X_2 = \sqrt{-\frac{1}{2\beta_2}}$. Hence, this is the point where the exogenous variable X_2 has the steepest negative slope and, thereby, the greatest influence on the endogenous variable, Y_1. The interpretation is similar for X_3. See figure 3 for an illustration of a simple version of the exponential function in (1) including the inflection point.
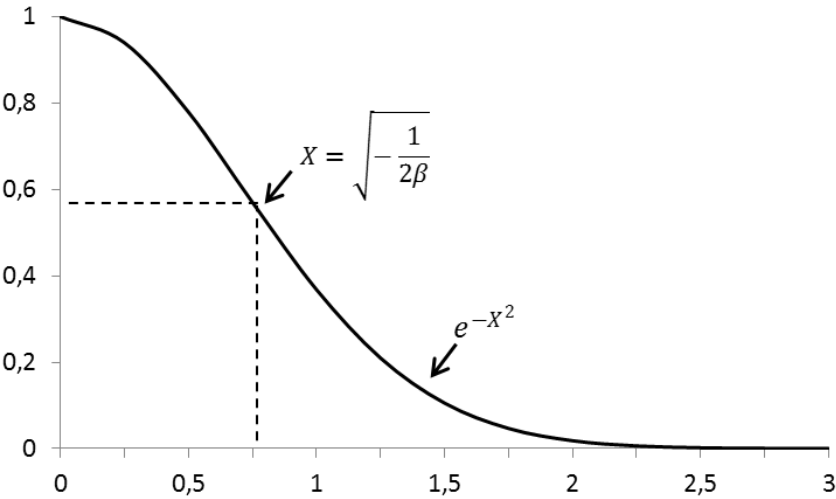

Figure 3: Illustration of the exponential function

The specification chosen has the advantages of handling the zero values of the measured variables and providing fairly simple interpretations of the estimated coefficients in terms of percentage change in the average speed (Hensher & Brewer, 2001). In addition, the log-transformation of traffic speed

allows the model to handle interaction between the weather variables. For example, since $\partial Y_1/\partial X_2 = 2\beta_2 X_2 e^{\beta_0+\beta_1 X_1+\beta_2 X_2{}^2+\beta_3 X_3{}^2+\beta_4 Y_2+\beta_5 Y_3}$, the effect of a change in wind speed on traffic speed depends on the level of the other to weather indicators as well. In equation (1), it is assumed that parameter β_0 is positive, while the sign of all other parameters is expected to be negative. Since all the weather indicators are assumed to negatively influence traffic speed, the cross-derivatives will be positive[4]. This implies, e.g., that the negative effect of wind on traffic speed is moderated for higher values of precipitation and if temperature is approximately 0°C. Hence, increase in wind speed will have greater effect on traffic speed in weather with no precipitation or temperatures around freezing point, than would be the case when traffic speed is already reduced by these other weather factors.

In equation (2), it is assumed that all parameters are positive. Literature supports the assumption that demand for freight transport is less vulnerable to adverse weather than the demand for passenger transport (Button, 2010), therefore the proportion of heavy vehicles is assumed to increase in adverse weather. The constant term in equation (3) is assumed to be negative, otherwise the parameters are assumed to be positive.

In order to estimate SEM, covariance analysis methods are used which are based on minimising the difference between the sample covariance and the model implied covariance matrices (de Oña, de Oña, Eboli, & Mazzulla, 2013). In our analysis a standard linear SEM was used and the parameters were estimated by the Maximum Likelihood method (ML)[5]. This is the most frequently used estimation method (de Oña et al., 2013; Golob, 2003). Although the linear SEM with ML estimation assumes normally distributed variables, the method has proven to be robust to non-normality in the variables if the sample size is large enough (Golob, 2003). Large samples are also favourable when the data is kurtotic, as in our example. Various suggestions have been proposed for what sample sizes can be regarded as sufficient (Golob, 2003). Since there are only 6 observed variables and 20 free parameters to be estimated, our sample size of 1176 is well beyond the proposed sizes for being adequate.

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[4] The impact of precipitation on the relationship between wind and average speed is given by $\partial^2 Y_1/\partial X_2 \partial X_3 = 4\beta_2\beta_3 X_2 X_3 Y_1 > 0$. Hence, when X_2 and X_3 represents wind and precipitation, respectively, then more precipitation would reduce the negative influence of wind on speed. The elasticity, $EL_{Y_1} X_2 = 2\beta_2 X_2{}^2$, becomes more negative when the value of X_2 increases. The interpretation is similar for the elasticity with respect to X_3.
[5] The presence of nonlinear relationships suggests the use of a generalized model. However, estimating the model by generalized SEM gave estimation results very close to the results obtained by linear SEM with ML (all coefficients obtained by generalized SEM were within the 95% confidence interval of the linear SEM estimates). Because of the similarity in results, our large sample size, and the fact that the standard linear SEM is most frequently applied, at least within transportation research, we will present the results from the standard linear SEM.

3.2 Classification and Regression Tree (CART)

Classification and Regression Trees (CART) is a methodology well suited to deal with large data sets, nonlinear relationships, high-order interactions, and missing values (De'Ath & Fabricius, 2000). A single response variable is explained by repeatedly splitting the data into more homogenous groups, using combinations of explanatory variables (De'Ath & Fabricius, 2000). When the response variable is numerical, like *speed* in this study, the procedure is known as regression tree, while it is known as classification tree when the response variable is categorical (Questier, Put, Coomans, Walczak, & Heyden, 2005).

CART is a statistical technique that can select from a large number of explanatory variables (x) those that are most important in determining the response variable (y) (Questier et al., 2005). It is a form of binary recursive partitioning procedure (Lewis, 2000). The steps in the analysis can be summarized as follows: First, all objects are assigned to a root node (Questier et al., 2005). Second, the CART software finds the best possible variable to split the node into two child nodes. In order to find the best variable, all possible splitting variables and all possible values of the variables are checked (Lewis, 2000). The variable and split point with the highest reduction of impurity of the node is selected (Questier et al., 2005). The impurity of the node can be defined as the total sum of squares of the response values around the mean of the node. For a node with *n* objects, the impurity is then defined as (Questier et al., 2005):

(4) $impurity = \sum_{i=1}^{n}(y_i - \overline{y})^2$

After the parent node is split into the two child nodes, these two child nodes each become new parent nodes, and split according to the same procedure above. The procedure is repeated until the tree has maximum size (Questier et al., 2005). The tree is represented graphically which makes the interpretation of the result relatively easy.

There are different ways of stopping the tree building (Lewis, 2000). In this study, an external limit has been set to include only the levels where the split of the nodes creates groups that differ significantly at the 5% level, and the process is stopped at the fourth level.

In general, the CART analysis has not been widely used. This is possibly due to poor implementation in the leading statistical packages Lewis (2000). However, some examples of the use of the CART methodology in transportation research exist. Stewart (1996) applied this method to a highway safety analysis. For this study the ability of CART of dealing with large number of independent variables and identifying complex interactions among the variables affecting highway safety, was exploited. Abdel-Aty et al. (2005) used the CART methodology to study the different factors that affect crashes at

signalized intersections. The methodology was adopted because of its ability to cope with multicollinearity between variables, missing observations, and the fact that the true model form was unknown (Abdel-Aty et al., 2005).

Particularly two characteristics of this study make the CART methodology suitable as an analytical tool. First, we are dealing with nonlinear relationships, and second, the true model of the relationship between the independent variables and the dependent variable is unknown.

4. Results and discussion

4.1 Structural Equation Modelling

In Table 4 goodness-of-fit statistics for the chosen SEM model are listed. The Chi-Square statistics indicates that we cannot, at a 5% level, reject that the model fits as well as the saturated model. The RMSEA has a value of 0.000 which indicates good fit. Values up to 0.07 are normally considered to be satisfactory (D. Hooper, Coughlan, & Mullen, 2008). Finally, a CFI equal to 1.000 and a SRMR well below 0.05 also indicates good model fit. All together, the goodness-of-fit statistics supports that the SEM model is appropriate.

Table 4: Goodness-of-fit statistics

Goodness-of-fit statistics	Value	Description
Likelihood ratio		
Chi2(1)	0.280	Model vs. saturated model
p > chi2	0.596	
Population error		
RMSEA	0.000	Root mean squared error of approximation
90 % conf.int., lower bound	0.000	
upper bound	0.062	
Baseline comparison		
CFI	1.000	Comparative fit index
Size of residuals		
SRMR	0.004	Standardized root mean squared residuals

The results from the estimation of the model are presented in Table 5. All coefficients have signs according to the *a priori* assumptions. All the direct effects of the weather variables, proportion of heavy vehicles, and convoy, on traffic speed, were significant at the 1% level for all coefficients except temperatures around freezing point which was significant at the 5% level. The effects of the weather variables on convoy were, as expected, all significant at the 1% level, while the results indicate that the weather variables do not influence the proportion of heavy vehicles that strongly. Only the effect of precipitation was significant at the 5% level.

According to the model, wind speed of 19.6 m/s has the greatest marginal effect on traffic speed (the inflection point illustrated in Figure 3). From the descriptive statistics in Table 2, we see that the maximum wind speed measured in the studied time period was 19.1 m/s. This measurement indicates that wind speed had an increasing effect on traffic speed in all the observations in our study. Similarly, precipitation at the level of 5.3 mm/h had the greatest marginal effect on traffic speed. This level is also above the maximum precipitation of 4.5 mm/h measured in our study (see Table 2).

Table 5: Model results

		Coefficient	Std. Error	z	P>|z|
Structural:					
Y_3 (convoy) $<-$					
	X_2^2	0.00108	0.00012	8.68	0.000
	X_3^2	0.02195	0.00523	4.19	0.000
	X_1	0.03722	0.01265	2.94	0.003
	Constant	-0.02462	0.00990	-2.49	0.013
Y_2 (heavy) $<-$					
	X_2^2	0.00024	0.00015	1.54	0.123
	X_3^2	0.01398	0.00649	2.15	0.031
	X_1	0.02577	0.01569	1.64	0.100
	Constant	0.37063	0.01228	30.18	0.000
lnY_1 (ln-speed) $<-$					
	Y_3	-0.21138	0.02280	-9.27	0.000
	Y_2	-0.17441	0.01839	-9.48	0.000
	X_2^2	-0.00133	0.00010	-13.26	0.000
	X_3^2	-0.01771	0.00413	-4.29	0.000
	X_1	-0.02164	0.00994	-2.18	0.029
	Constant	4.49269	0.01034	434.66	0.000
Variance:					
	$e. Y_3$	0.04187	0.00173		
	$e. Y_2$	0.06437	0.00265		
	$e. Y_1$	0.02559	0.00106		

To illustrate the results from the analysis, Table 6 predicts some traffic speed values under various weather conditions. The model predicts wind to have the greatest impact on traffic speed, closely followed by precipitation. However, the effect of temperatures around freezing point seemed to be of only minor importance in our study. It is not surprising that wind and precipitation had the largest effect on traffic speed. Snowdrifts are identified by the NPRA (2012) as the main problem when striving to keep the road open for traffic in the winter months. As Table 6 shows, maximum wind alone can cause a 43% reduction in traffic speed compared to perfect driving conditions. The model predicts a 68% reduction in traffic speed in the situation with a combination of maximum wind and precipitation

and, in the worst-case scenario with all three weather variables being maximum unfavourable, the reduction is 69%.

Table 6: Predicted impacts of adverse weather conditions on average traffic speed (calculations are based on the variable characteristics in Table 2 and model results in Table 5)

Weather condition	Average traffic speed	Decrease in average traffic speed in relation to perfect driving conditions
Perfect driving conditions (X_1=0, X_2=0, X_3=0)	84 km/h	
Maximum wind (X_1=0, X_2=19.1, X_3=0)	48 km/h	43%
Maximum precipitation (X_1=0, X_2=0, X_3=4.5)	54 km/h	36%
Temperatures at approximately 0 °C (X_1=1, X_2=0, X_3=0)	81 km/h	3%
Maximum wind and maximum precipitation (X_1=0, X_2=19.1, X_3=4.5)	27 km/h	68%
Maximum wind and temperatures at approximately 0 °C (X_1=1, X_2=19.1, X_3=0)	46 km/h	45%
Maximum precipitation and temperatures at approximately 0 °C (X_1=1, X_2=0, X_3=4.5)	52 km/h	39%
Maximum precipitation, maximum wind and temperatures at approximately 0°C (X_1=1, X_2=19.1, X_3=4.5)	26 km/h	69%

4.2 CART analysis

The CART analysis explained 34% of the variation in average traffic speed. The results from the analysis are presented in Figure 4. Starting at the top of the figure we can see that the weather variable that best split the root node into two child nodes was wind speed. At the end of each branch in the regression tree, the number of vehicles (n) and their average speeds are shown. In 30 of the observations the wind speed was equal to or above 13.85 m/s, and for 12 of these observations the weather was considered unfit for free movements of vehicles and traffic was then led in convoys. The average traffic speed for these vehicles was only 35 km/h. In the remaining 18 observations the average speed was 60 km/h.
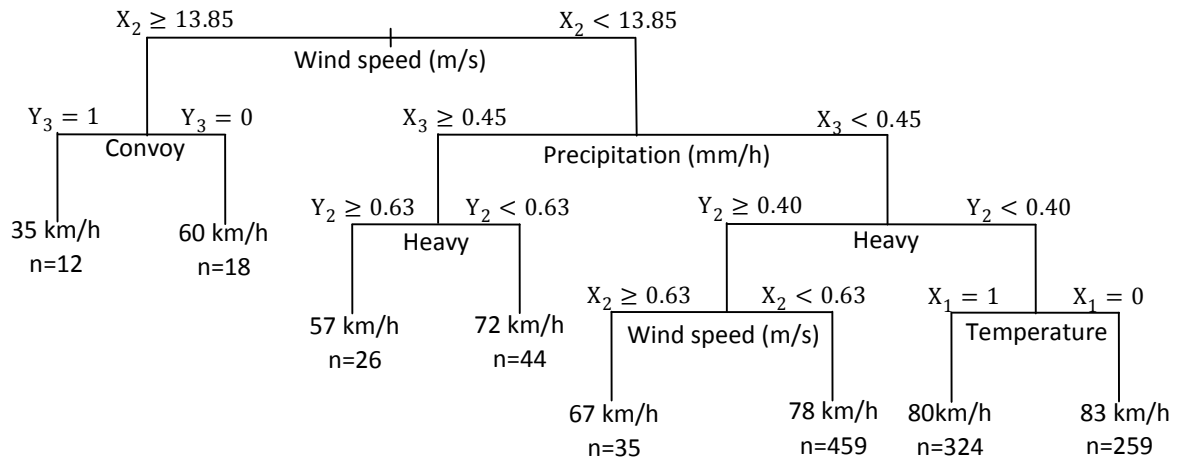
X_2 ≥ 13.85 ⎸ X_2 < 13.85

$X_2 \geq 13.85$ $X_2 < 13.85$

Wind speed (m/s)

$Y_3 = 1$ $Y_3 = 0$ $X_3 \geq 0.45$ $X_3 < 0.45$

Convoy   Precipitation (mm/h)

35 km/h   60 km/h $Y_2 \geq 0.63$ $Y_2 < 0.63$ $Y_2 \geq 0.40$ $Y_2 < 0.40$

n=12   n=18   Heavy   Heavy

57 km/h   72 km/h $X_2 \geq 0.63$ $X_2 < 0.63$ $X_1 = 1$ $X_1 = 0$

n=26   n=44   Wind speed (m/s)   Temperature

67 km/h   78 km/h   80km/h   83 km/h

n=35   n=459   n=324   n=259

Figure 4: Results from the CART analysis. The average traffic speed is shown at each node endpoint, and n equals the number of observations with this average traffic speed.

For wind speeds below 13.85 m/s, the figure shows that precipitation was the next weather variable splitting the node best. When precipitation was equal to or above 0.45 mm/h, the average traffic speed was 57 km/h for 26 of the vehicles and 72 km/h for 44 vehicles. We can see that the group of vehicles where the proportion of heavy vehicles was large ($Y_2 \geq 0.63$) had the lowest average traffic speed. The result indicates that the average traffic speed of heavy vehicles is more vulnerable to precipitation than private motor vehicles.

According to the CART analysis, temperatures around freezing point had but a minor effect on traffic speed. If we follow the branch from the right top to the right bottom of the figure (for the observations where wind speed was below 13.85 m/s, precipitation was below 0.45 mm/h, and the proportion of heavy vehicles was below 0.40), we can see that temperatures around freezing point only caused a reduction in average traffic speed of 3 km/h compared to the situation with temperatures above or below freezing point.

4.3 Comparison of the two analytical approaches

Both the SEM and the CART analysis showed similar results with regard to the effect of the various explanatory variables. Wind seems to be the most influential weather indicator on traffic speed with precipitation following close behind. A little surprising was the small effect temperatures around freezing point had on traffic speed. This may, however, be due to the characteristics of the road section at which our traffic counting was conducted. The electronic counter used in the analysis is located at a relatively flat and not curved road section. Temperatures around freezing point have been identified by road users as creating difficult driving conditions because temperatures around freezing point are

associated with slippery roads (Hagen & Engebretsen, 1999). However, the effect of slippery roads on traffic speed is probably most problematic on steep, narrow and winding roads.

The magnitudes of the decrease in average traffic speed differs slightly in Table 6 (calculations of effects of adverse weather on traffic speed based on the regression analysis) and the CART analysis in Figure 4, but this is mainly because the values in Table 6 are the result of maximising the weather indicators, while the results presented in Figure 4 are average values of traffic speed for several observations with similar weather characteristics.

5. Benefits of reducing winter problems on mountain passes

In order to illustrate the value of the benefits the road users would experience if the winter problems on the mountain pass were reduced, we have made a numerical example (see Table 7). The example relates to the 20 km long road section between the road-barriers at each side of the mountain pass studied. The road barriers are used to hold traffic when the weather is too severe for the free movement of cars. The speed limit is 80 km/h where our study was conducted, while the speed limit is 90 km/h between the two road barriers. We have assumed that, in adverse weather, people adjust their speed to meet the difficult driver conditions and that the speed limit will have a limited influence on speed choice.

The benefits related to reducing weather problems in our case have been calculated according to the NPRA (2008) guidelines for calculating CBAs of new transport projects. The value of travel time savings for private motor vehicle transport used (372 NOK/h/ 44.69 EUR/h[6])[7] is a weighted average value per vehicle per hour for business, commuter, and leisure traffic for the average situation related to long distance travels (> 100 km). The time dependent transport cost per hour used for heavy vehicles (546 NOK/h/ 65.59 EUR/h) is a weighted average between lorries and tractor-trailer vehicle combinations[8] in accordance with NPRA suggestions (2008). For simplicity, 40% of the total traffic is considered to be heavy vehicles (see descriptive statistics in Table 2) even though the CART analysis indicates that the proportion of heavy vehicles differs between the various speed groups (see Figure 4).

For the numerical example we used the results from the CART analysis presented in the regression tree in Figure 4. In the regression tree the observations are grouped with regard to similar weather

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[6] 1 Euro = 8.324 NOK, June 23, 2014 (Norwegian Central Bank, 2014).
[7] Unit prices according to NPRA (2008) 's guidelines were adjusted to the November 2013 level by the consumer price index (SSB, 2013)
[8] The variable Y_2 (heavy vehicles) in our study may contain lorries, buses, and tractor-trailer vehicle combinations. The proportion of buses is omitted because it is expected to be very low because the time period studied is outside the tourist season.

characteristics. We used these groups of observations to calculate the average time cost experienced by the vehicles under various weather conditions. Only the observations with average speed below the speed limit of 80 km/h (average speeds equal to 78 km/h or lower in the CART analysis) were included in the numerical example. The numbers were adjusted to reflect the total population and traffic in both directions and relate purely to the three winter months represented by the empirical data.

Table 7: Time costs between Bolnastua (southern side of Saltfjellet) and Sørelva (Northern side of Saltfjellet) (20 km) for vehicles with reduced traffic speed due to adverse weather. The weather conditions with corresponding average speed and number of vehicles relate to the CART analysis (see Figure 4).

Weather conditions	Average speed (km/h)	No of vehicles	Time costs heavy vehicles (NOK)	Time costs passenger traffic (NOK)	Time costs heavy and passenger vehicles (NOK)
Prec. < 0.45 mm/h, wind < 10.75 m/s, heavy ≥ 0.4	78	16 289	913 586	932 640	1 846 226
Prec. ≥ 0.45 mm/h, wind < 13.85 m/s, heavy < 0.63	72	1 561	94 875	96 854	191 729
Prec. < 0.45 mm/h, wind ≥ 10.75 m/s, heavy ≥ 0.4	67	1 242	81 101	82 792	163 893
Wind ≥13.85 m/s, not convoy	60	639	46 575	47 546	94 121
Prec. ≥ 0.45 mm/h, wind ≥ 13.85 m/s, heavy ≥ 0.63	57	923	70 816	72 293	143 108
Wind ≥13.85 m/s, convoy	35	426	53 229	54 339	107 567
Total in NOK		21 080	1 260 181	1 286 463	2 546 645
Total in EUR			151 391	154 549	305 940

The difference between the time cost experienced by the vehicles in our study (2,546,645 NOK/305,940 EUR) and the time cost when the vehicles are able to drive by the speed limit (2,071,000 NOK/248,800 EUR) is defined as the value of the benefit of removing the impact of adverse weather on traffic speed. This benefit amounts to 476,000 NOK (57,200 EUR). This calculation only relates to the three winter months studied and the 20 km road section at the top of the mountain. These estimates could be extended to include the whole winter season (defined as the period from October 16th to May 1st 2014, see footnote 2) and the entire mountain area. The calculated benefit then amounts to 2,348,000 NOK (282,100 EUR) every winter. Consequently, if we could implement measures which removed adverse weather impact on traffic flow, the drivers crossing the whole mountain area would experience travel time savings valued at 2,348,000 NOK (282,100 EUR) every winter. The net benefit of a CBA of such a project would increase approximately 46.5 million NOK (5.59 million EUR)[9] if these travel time savings were included. Examples of such projects in the context of this study are: a tunnel through the mountain to avoid the mountain pass, building of road

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[9] In CBAs of road projects in Norway the costs and benefits are discounted 40 years with a discount rate of 4%.

superstructures at particularly exposed areas, improvements of the road structures etc. To state explicitly the value of reducing the impact of adverse weather on traffic flow could also ease the justification of spending more resources on operating and maintaining the road section.

Two effects of adverse weather on traffic not investigated in this study are the effects on travel time reliability and material wear. The transport of perishable goods, such as fresh fish (which is an important export commodity in this region of Norway), depends on fast and reliable transport (Hanssen & Mathisen, 2011). Because of the short selling time frame, a one-day delay can have a large impact on the value of fresh fish. Hagen and Engebretsen (1999) estimated the inconvenience costs related to delays and uncertainty for freight transport in winters at Korgen[10] (a mountain pass a little further south of Saltfjellet) to be on average 80 NOK (9.61 EUR) per travel[11]. When applying these estimates to the case of Saltfjellet, the corresponding total inconvenience costs for heavy vehicles for the whole 2011/2012 winter season were approximately 3.5 million NOK (421,200 EUR). In addition, the winter roads at mountain passes cause extra material costs due to the necessity of using spike tires and chains. There is also extra wear on breaks and engines (Hagen & Engebretsen, 1999). In a CBA of a project aimed at reducing the winter problems the reduction in inconvenience costs would increase the net benefit of the project even further.

The value of the benefit of reducing adverse weather impact on traffic flow calculated in our numerical example is conservative. First, the unit prices used to calculate the value of travel time savings for passenger traffic are probably too low. They are average unit prices (NPRA, 2008) which do not consider the effect of different driving conditions. Tseng and Verhoef (2008) showed that individuals' willingness to pay for travel time savings is time-dependent. Similarly, there are reasons to believe that people perceive the situation of being in a snowstorm on a mountain pass as risky and therefore value one hour of saved travel time in a snowstorm on a mountain pass more highly than one hour of saved travel time in nice weather. Higher valuation of travel time savings on mountain passes would increase the net benefit of projects reducing weather related problems.

The second reason why we consider the calculated benefit above to be conservative is that we have assumed that traffic will normally have an average speed equal to the speed limit when the weather is nice. However, the SEM analysis showed that the average speed was 4 km/h above the speed limit

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[10] Korgen was a mountain pass facing the same kind of winter problems as Saltfjellet, but a new tunnel in 2005 reduced the problems. The benefits of reduced weather problems were not considered when calculating the value of the project.
[11] This cost estimate included the extra time needed to put on chains before crossing the mountain pass. This was assumed to be necessary every day in the winter months at Korgen.

under perfect driving conditions. This indicates that that the actual difference in time costs in good and adverse weather is larger than estimated in our example.

The road sections on the southern and northern side of Saltfjellet are highly curved, narrow, and steep. As discussed earlier, traffic flow on these road sections is likely to be even greater affected by adverse weather than revealed at the straight, low gradient road section where our analysis was conducted. This is a third reason why we consider the estimated benefit above to be conservative.

Finally, most climate researchers agree that the climate is changing (Doran & Zimmerman, 2009), and research on climatic change predicts increased amounts of precipitation and higher temperatures in Norway for the next few decades. Moreover, the frequency of extreme weather incidents is expected to increase. Research indicates an increase in number of episodes with strong wind, but because of lack of data, these results are uncertain (NOU 2010: 10, 2010). Since temperatures are mostly below freezing point during winter at Saltfjellet, the increase in precipitation will take the form of snow and there will be more days with temperatures around freezing point at this time of year. Consequently, adverse weather impact on traffic flow will probably increase in the future.

6. Conclusions and implications

In this paper, we have studied how temperature, wind, and precipitation impact traffic flow, represented by traffic speed, on a mountain pass located in Northern Norway. Two different methodologies have been applied—structural equation modelling (SEM) and classification and regression tree (CART) analysis. According to the results of both analyses traffic speed was significantly reduced by weather conditions with strong wind, temperatures around freezing point, and precipitation. The two methods supported each other both in the interpretation and validation of the impact of weather on traffic flow.

Adverse weather have large impact on traffic on mountain passes today and the impact will most likely increase in the future due to anticipated climate change. Adverse weather impacts traffic flow in two important ways. First, when traffic speed is lowered, the vehicles spend more time making the trip, and second, the travel times become unreliable. The mountain pass studied, and many similar mountain passes in Norway, are defined as major national transport corridors with few or sometimes practically no alternatives. Both freight transport and private motor vehicles depending on these transport routes would experience great benefits from projects increasing the efficiency and reliability of these road sections. A typical example of such a project is to build a tunnel through the mountain to avoid a problematic mountain pass. Even though the aim of the CBAs is to consider all benefits and costs of projects, the weather-related benefits revealed in this study are not included today. In this

study we have shown that these benefits can be significant and we therefore argue that they are highly relevant to include. The mountain passes are low traffic roads and when the benefits of projects on these roads are calculated in the traditional way, the outcome is often low compared to projects in more densely populated area. It is therefore important to include the weather related benefits because then the result of the CBAs would give a more exact estimate of the total benefits for society and make it easier for decision makers to compare the benefits and costs of different projects. We fear that in the fight for scarce resources, initiatives aimed at reducing weather-related problems could lose if the benefits they produce are not taken into consideration by the calculation tools.

Although we have focused this study on traffic problems on mountain passes, other parts of the transport system experience similar problems due to adverse weather. Several road sections are exposed to the risk of avalanches and mudslides caused by intense precipitation, and the ferries used for fjord crossings sometimes have to cancel trips due to adverse weather. This threatens the efficiency and reliability of the transport system. Taking into account the expected change in climate, knowledge and consideration of adverse weather impact on the transport system is therefore of vital importance when planning future transport. Fortunately, there is increasing awareness of how climate change and problems related to climate will affect all parts of society, including the transport system. Several projects have been conducted with the aim of mapping challenging areas of the transport system in order to be able to be more proactive in the response to the expected climate change. One example is the interdisciplinary research project InfraRisk (2013) in which the impacts of extreme weather events on infrastructure in Norway has been studied. The project concludes that frequent disruptions of the transport system have large economic consequences and that economically it is preferable to have a proactive approach to the problems rather than a reactive approach. However, it is necessary to investigate which measures to initiate and when in order to be sure that resources are used effectively.

Admittedly, it is a weakness that it has only been possible to study the impact of adverse weather on a straight and wide road section because of the location of the electronic counter. A topic for further research is to study the effect of adverse weather on traffic flow at narrow road sections with curvature and steep hills since these parts of the road are likely to be even greater affected by adverse weather than what is revealed in our study. In addition, this study has only studied the impact of adverse weather on traffic flow. The literature suggests that adverse weather affects travel behaviour in other ways, too. A second suggestion for further research is to study the impact of adverse weather on route choice and travel demand as well.

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