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Effects on accidents of changes in the use of studded tyres in major cities in Norway: a long-term investigation

Rune Elvik[a,b], Lasse Fridstrøm[a], Joanna Kaminska[c], Sunniva Frislid Meyer[a]

a Institute of Transport Economics, Gaustadalléen 21, NO-0349 Oslo, Norway

b Department of of Planning and Development, Aalborg University, Fibigerstræde 13, DK-9220 Aalborg Ø., Denmark

c Department of Mathematics, Wroclaw University of Environmental and Life Sciences, PL-50-357, Wroclaw, Poland

ABSTRACT

This paper reports the findings of two studies made eleven years apart in Norway (Fridstrøm 2000, Elvik and Kaminska 2011) to evaluate effects on accidents of changes in the use of studded tyres in major cities in Norway. The first study covered the period from 1991 to 2000, the second study covered the period from 2002 to 2009. In both these periods, large changes in the percentage of cars using studded tyres were found in the cities that were included in the study. There was, in most cities, a tendency for the use of studded tyres to go down. Effects of these changes on injury accidents were evaluated by means of negative binomial regression models, using city and day as the unit of analysis, and including more than twenty explanatory variables in order to control for confounding factors. The effects of changes in the percentage of cars using studded tyres were well described by an accident modification function (dose-response curve), relating the size of changes in the number of accident to the size of the change in the use of studded tyres. Accidents during the season when the use of studded tyres is permitted were found to increase by about 5 percent if the use of studded tyres was reduced by 25 percentage points (e.g. from 50 to 25 percent) and to decline by about 2 percent when the use of studded tyres increased by 20 percentage points.

Key words: studded tyres, evaluation study, cities, negative binomial regression, accident modification function

1 INTRODUCTION

Studded tyres have been used in winter in the Nordic countries since the nineteen-sixties. Their use is controversial, because the studs tear off micro-particles from the road surface. The spread of these particles causes pollution and the smallest particles can be inhaled and represent a health hazard. The first study examining the effects on public health of the suspension of micro-particles in the air (Rosendahl 1996) estimated that this caused 90 premature deaths annually in the city of Oslo. Use of studded tyres was estimated to account for about 28 percent of the total amount of micro-particles. Since the nineteen-nineties, the use of studded tyres has therefore been discouraged in major cities in Norway. Some cities have introduced a tax for using studded tyres. This paper presents the results of two evaluation studies that were made to determine the effects on accidents of changes in the use of studded tyres. The first study was reported in 2000 (Fridstrøm 2000). It covered the period from 1991 to 2000 in the cities of Oslo (population in 2011: 600,000), Bergen (population in 2011: 260,000), Trondheim (population in 2011: 175,000) and Stavanger (population in 2011: 130,000). The second study was published in 2011 (Elvik and Kaminska 2011). It covered the period from 2002 to 2009 in the same four cities as the first study, with the addition of the city of Drammen (population in 2011: 65,000).

The second study was intended as a replication of the first study. It was therefore, as far as possible, identical to the first study in terms of the data collected and the statistical analyses performed. The results of the two studies are regarded as comparable. The main research question of this paper is:

What are the effects on accidents of the changes in the use of studded tyres that have taken place in major Norwegian cities in the period from 1991 to 2009?

The study aims to establish a causal relationship. The results will therefore be discussed by reference to criteria of causality.

2 REVIEW OF PREVIOUS STUDIES

The use of studded tyres on motor vehicles during winter is common in Norway, Finland and Sweden. Studded tyres are mainly intended to enhance friction and thereby improve safety. A meta-analysis of studies reported before 1999 (Elvik 1999) concluded that cars using studded tyres have a slightly lower accident rate per kilometre of driving (about 4 percent lower) during winter than cars using other types of tyres. The difference in accident rate was not statistically significant at conventional levels. The study found that the effect attributed to studded tyres was strongly related to study quality. Larger effects were reported in studies with poor control for potentially confounding factors than in more well-controlled studies.

The meta-analysis also summarised the findings of studies that have evaluated the effects of laws banning the use of studded tyres. Such laws have been passed in some states in the United States of America, some provinces in Canada and the northern part of Japan. Banning the use of studded tyres was associated with a small increase in the number of accidents in winter, roughly 4 %, according to the most recent evidence from Hokkaido in Japan.

Thus, studies performed before 2000 agree that the use of studded tyres does confer a small safety benefit. Reducing the use of studded tyres was found to be associated with a small increase in the number of accidents. A recent study by Strandroth et al. (2012) estimated the effect of studded tyres on fatal accidents to be a reduction of 42 % on roads covered by snow or ice and an increase of 6 % on dry or wet road surfaces. No previous study has reported the effect of studded tyres on fatal accidents. It is therefore difficult to compare the findings of this study to previous studies.

3 DATA AND METHODS

3.1 Sample of cities and variables included in study

The first study (Fridstrøm 2000) included the cities of Oslo, Bergen, Trondheim and Stavanger. The duration of the study period varied from city to city. It was from 1991 to 2000 in Bergen and Stavanger, from 1992 to 2000 in Trondheim (the 1995-1996 winter season was omitted) and from 1993 to 2000 in Oslo. The second study (Elvik and Kaminska 2011) included the same cities as the first study with the addition of the city of Drammen. The study period was from 2002 to 2009 in all cities, but the years 2003 and 2004 were omitted from the analysis for the city of Drammen. City and day was used as unit of analysis in both studies.

The variables for which data were collected are listed in Table 1. A distinction is made between five groups of variables. In the analyses reported in this paper, only one of the dependent variables was used (injury accidents). The analyses using insurance reported accidents as dependent variable were based on an estimated number of accidents per day, not a real count, and did not produce very clear findings, possibly as a result of poor data. There are several problems with these data: (1) If more than one car is involved in an accident, it is likely that more than one claim will be filed. It is therefore necessary to convert the number of claims to an estimated number of accidents. (2) For single vehicle accidents, there will be under-reporting, as only cars with collision insurance, which is voluntary in Norway, will have any insurance coverage for this type of accident. (3) The level of reporting could, in theory, be related to other variables included in the study, such as weather conditions, as single-vehicle accidents may be more likely to occur when there is snow and roads are slippery.

Table 1 about here

All variables were identically defined and measured in the two studies except for the length of daylight. In the first study, daylight was measured by means of a sinus curve taking the value of –1 at midsummer (summer solstice), 0 at equinox and +1 at midwinter (winter solstice). In the second study, daylight was measured by the share of 24 hours during which the sun was above the horizon. Both the sinus curve and the hours of sunshine were city-specific (since the cities were located at different latitudes).

3.2 Principal sources of data

Several sources of data were combined. Data on the number of police reported injury accidents were taken from the STRAKS accident record, which is kept by the Public Roads Administration. The Public Roads Administration also provided data on traffic volume and the mean speed of traffic. These data are recorded by automatic traffic counting devices based on inductive loops buried in the road surface.

Data on the use of studded tyres were taken from counts made by the Public Roads Administration in the second week of February every year. These counts were assumed to represent the peak use of studded tyres during the season. In the first study, a richer data set on the use of studded tyres was obtained, permitting estimation of the daily use of studded tyres. In the second study, it was not possible to estimate the daily use of studded tyres. Peak use was assumed to remain constant throughout most of the season when the use of studded tyres is permitted. Rules were developed to estimate the use of studded tyres at the beginning and end of the season. These rules, based to a large extent on the estimates developed in the first study, were fairly complex and are not described in this paper (the report by Elvik and Kaminska, which can be downloaded free of charge from the website of the Institute of Transport Economics (https://www.toi.no/article30035-8.html), gives a complete description of the rules). Use of studded tyres is permitted from November 1 until Monday of the first week after Easter.

Data on daily minimum and maximum temperatures and precipitation were downloaded from the eKlima website, hosted by the Norwegian Institute of Meteorology. This website is freely accessible and contains time-series of data recorded at all weather stations in Norway.

3.3 Variable transformations

Some of the variables were transformed. The same transformations were used in both studies.

Readings of precipitation are normally taken only once per day (as opposed to temperature which is recorded several times per day). Precipitation is normally recorded at around 7 o'clock in the morning and refers to the past 24 hours. To get the correct amount of snow on a given day, the recorded values were adjusted as follows:

$$\text{Adjusted amount of snow} = \frac{7}{24} snow_{rt} + \frac{17}{24} snow_{rt+1}$$

Snow denotes the amount of snow, stated in millimetres, recorded in city r on day t. The new variable is referred to as "estimated snowfall" (abbreviated estsnow). This transformation was applied only to snow. As far as rain is concerned, the amount of rain recorded at 7 o'clock in the morning on day t was shifted backward to day t – 1, because it was assumed that rain falling between midnight and 7 in the morning would not have very much of an impact on traffic. This assumption is reasonable, because only a minor share of all traffic takes place between midnight and 7 in the morning. The new variable is referred to as "estimated rain" (abbreviated estrain). The effects of precipitation on the number of accidents have been modelled according to the following functions:

Function for snow = $-\frac{1}{\sqrt{(estsnow+0.1)}}$

Function for snowdepth = $-\frac{1}{\sqrt{(snowdepth+1)}}$

Function for rain = $-\frac{1}{estrain+0.5}$

Snowdepth was given in centimetres. Days were divided into three groups depending on the maximum and minimum temperatures. Days in which the temperature crossed zero are referred to as “crosszero”. These days are identified by means of a dummy variable which takes the value of 1 when zero degrees Celsius was crossed. The functional forms used for the weather-related variables were developed by means of exploratory analyses, comparing different functional forms in terms of likelihood ratio tests. The functional forms assume that weather has a decreasing marginal effect on accidents, e.g. the first 10 centimetres of snowfall will have a greater effect on accident rate than the next 10 centimetres, and so on.

The effects of studded tyres on accidents were captured by means of the following interaction terms:

Interaction with snow = function for snow · ln(percent use of studded tyres + 1)

Interaction with snowdepth = function for snowdepth · ln(percent use of studded tyres + 1)

Interaction with crosszero = dummy for crosszero · ln(percent use of studded tyres + 1)

The functions for snow and snowdepth are the transformed variables defined above. Ln is the natural logarithm. A constant one 1 has been added as a scaling parameter, since the natural logarithm of 1 equals 0. The variable will then assume the value of zero when the percent use of studded tyres is zero. The reason for specifying the effects of studded tyres in terms of these interactions is to avoid or minimise an omitted variable bias that may arise as a result of a possible correlation between the use of studded tyres and any variable exhibiting a clear seasonal pattern. Temperature and precipitation in the form of snow are examples of such variables.

3.4 Treatment of missing data

In the first study, three data files were created. The first and most complete of these spanned the period from May 1, 1990 to March 31, 2000. With complete records, this amounts to 14 488 observations (city days). Missing data on traffic volume and the use of studded tyres reduced the data set to 11 436 records. Periods with missing data were omitted from the analyses. The second data file, comprising the period from January 1, 1992 to December 31, 1999, contained 10 316 observations. This data file included records of property-damage-only accidents in addition to injury accidents. The third data file covered the same period as the second, but also included speed data. These data were somewhat incomplete and reduced the number of observations to 5 837.

In the second study, there were some gaps, all shorter than three months, in the data regarding traffic volume and speed. These gaps were filled by estimating values based on the seasonal variation in years that had complete data. It was assumed that seasonal variation in traffic volume and speed would be the same in all years. Temperature data were missing for the city of Drammen for a few short periods in 2002, many short periods in 2003 and most of the year 2004. Temperature enters the analysis in the form of a dummy variable that takes the value of 1 if zero degrees Celsius was passed at least once in a day, otherwise zero. Missing data for those parts of the year when temperature is unlikely to cross the freezing point is therefore no problem. It was judged unlikely that the temperature would cross the freezing point in the months of June, July and August. In 2002, data were missing for 14 days in November. There is a fairly high probability that the temperature may cross the zero point in November. Data for the years that had complete data were used to judge the probability of days with temperature crossing zero degrees Celsius. It was found that there was between 5 and 13 days crossing zero in the month of November in Drammen in the years from 2004 to 2008. In November 2002, precipitation in the form both of rain and snow was recorded nine days. The temperature was assumed to cross zero all these days.

For the years 2003 and 2004, there was too much missing data to replace by means of estimates based on years with complete data. The years 2003 and 2004 were therefore omitted for Drammen.

3.5 Assessing goodness of fit for negative binomial regression model

A standard negative binomial regression model was fitted. Values predicted by this model can be obtained by inserting coefficients into an exponential function:

Predicted number of accidents = $e^{\left(\sum_{i=0}^{n} \beta_i x_i\right)}$

Here, e is the exponential function (i.e. the base of the natural logarithms, 2.71828) raised to the power of the sum of coefficients (β_i) multiplied by the respective values of the independent variables (x_i). By inserting the values cell-by-cell into the exponential function, the predicted number of accidents can be obtained for every day in every city. Model goodness-of-fit was assessed in terms of the Elvik-index of goodness-of-fit (Fridstrøm et al. 1995). The Elvik-index is based on the over-dispersion parameter. The amount of over-dispersion found in a data set can be described in terms of the over-dispersion parameter, which is estimated as follows:

$$Var(x) = \lambda \cdot (1 + \mu\lambda) \qquad (1)$$

In equation 1 μ denotes the over-dispersion parameter. Solving equation 1 with respect to the over-dispersion parameter gives**:**

$$\mu = \frac{\frac{Var(x)}{\lambda} - 1}{\lambda} \qquad (2)$$

If the mean (λ) and variance (Var(x)) of the raw data (i.e. the empirical distribution of the count of accidents per city per day) are known, the over-dispersion parameter of the crude data can be estimated by applying equation 2.

Denoting the over-dispersion parameter of the raw data as μ_{crude} and the over-dispersion parameter of the fitted model as μ_{model} the Elvik index is defined as follows:

Elvik-index of goodness-of-fit = $1 - \frac{\mu_{model}}{\mu_{crude}}$ (3)

It takes on values between 0 and 1 and shows the share of systematic variation in accident counts explained by the model.

3.6 Establishing the counterfactual by means of sample enumeration

The effect on accidents of changes in the use of studded tyres was estimated by means of the sample enumeration method. This method was chosen because it is suitable for answering the basic question of the evaluation:

What would have happened if the use of studded tyres had not changed?

The answer to this question represents the counterfactual condition that any evaluation study needs to establish if a causal inference is to be made (Heckman 2008). In this study, the counterfactual is defined as the use of studded tyres that was observed in the first year of the study. Thus, in the second study, 2002 was the first year. For the city of Oslo, counterfactual and actual use of studded tyres becomes:

Year	Actual use	Counterfactual use
2002	32.0	32.0
2003	28.4	32.0
2004	28.0	32.0
2005	23.8	32.0
2006	19.3	32.0

2007	19.5	32.0
2008	16.2	32.0
2009	16.5	32.0

In other words, the effects of changes in the use of studded tyres is estimated by comparing the estimated number of accidents assuming the observed changes in the use of studded tyres had not taken place, but all other factors had changed as observed after 2002 to the estimated number of accidents given the observed changes (in general reduction) in the use of studded tyres.

To give an example: The estimated number of accidents in Oslo from 2002 to 2009 was 7207.3. By replacing the actual use of studded tyres each year by the use in 2002, the number of accidents was estimated to be 7146.3. Thus, if the reduction in the use of studded tyres had not taken place, there would have been slightly fewer accidents than the number that was estimated given the reduction in the use of studded tyres. The difference is 7207.3 − 7146.3 = 61 accidents.

The statistical significance of this change was assessed by applying the following test. The standard error of the difference between the expected values of two Poisson distributions can be approximated as:

Standard error = $\sqrt{N_{act} + N_{counter}} = \sqrt{7207.3 + 7146.3} = 119.8$

This test accounts for random variation in the number of accidents only.

4 RESULTS

4.1 Changes in the use of studded tyres

Changes in the percentage of cars using studded tyres are shown in Table 2. It is seen that the use of studded tyres was considerably higher during the period covered by the first study than during the period covered by the second study.

Table 2 about here

During both periods, there were large changes in the use of studded tyres and large variation between cities with respect to the percentage of cars using studded tyres. There is, in other words, sufficient variation both over time and between cities to detect effects of the changes. There is a trend for the use of studded tyres to be reduced. However, there were also years in which the use of studded tyres increased compared to the previous year.

As part of the second study, a model was developed to explain changes in the use of studded tyres during the period from 2002 to 2009. A linear regression model was developed in order to estimate the effects of factors influencing the use of studded tyres. The model included year, city dummies, dummy for season of use of studded tyres and dummy for the presence of a tax on the use of studded tyres as independent variables. The percentage of cars using studded tyres was used as dependent variable. Table 3 reports the coefficients estimated.

Table 3 about here

It can be seen that there is a trend for the use of studded tyres to be reduced by about 0.8 percentage points every year. The introduction of a tax on the use of studded tyres reduces their use by about 4 percentage points.

4.2 Negative binomial regression models for injury accidents

Results of the negative binomial regression analyses are shown in Tables 4 and 5. Table 4 shows the coefficients estimated in the first study. Table 5 shows the coefficients estimated in the second study.

Tables 4 and 5 about here

Both models fitted the data very well. The Elvik-index measure of goodness-of-fit (Fridstrøm et al. 1995, Elvik 2011A) indicates that both models explain more than 90 percent of the systematic variation in the number of accidents per city per day. The values of the estimated coefficients are not identical in the two models, but most coefficients have the same sign in both models. The only noteworthy exceptions from this are the coefficients for the interaction between snowfall and use of studded tyres and the coefficients for Saturdays and Ascension weekend. The coefficients for daylight, although defined differently in the two models, indicate that a longer duration of daylight is associated with a lower number of accidents.

The coefficients intended to capture the effects of studded tyres tend not to be statistically significant at conventional levels. This does not necessarily mean that changes in the use of studded tyres have no effect on the number of accidents. The sample enumeration method has been applied in order to develop accident modification functions for changes in the use of studded tyres. Appendix 1 illustrates how to interpret the coefficients referring to the use of studded tyres.

4.3 Estimation of accident modification functions

The use of studded tyres is likely to influence the safety not just of the cars using such tyres, but also the safety of cars not using studded tyres. The reason for this is that the studs tear down snow or ice and thus clears the road surface more quickly of snow or ice than if studded tyres were not used (Krokeborg 1998). This means that a higher share of traffic takes place on bare road surfaces, which is an advantage for the safety of cars not using studded tyres. An earlier study (Krokeborg 1998) suggested that if the share of cars using studded tyres becomes very small, say, less than 20 percent, the benefits of the studs in wearing down snow or ice will be considerably reduced or lost.

If changes in the use of studded tyres cause changes in the number of injury accidents, one would expect the following regularities to be observed:

1. When there is a reduction in the use of studded tyres, the number of accidents will increase.
2. When there is an increase in the use of studded tyres, the number of accidents will decrease.
3. The larger the changes in the use of studded tyres, the larger the changes in the number of accidents.

4. If the use of studded tyres is reduced to less than 20 % of vehicles, there may be a larger increase in the number of accidents, as the effect of studded tyres in wearing down snow or ice is then reduced.

To test if there is such a pattern, a baseline year was defined in each city (the first year included in the study) and changes in the number of accidents associated with changes in the use of studded tyres in subsequent years were estimated by means of the sample enumeration method. As an example, the season 1991-1992 was the first one in the city of Stavanger. In the next season, use of studded tyres increased from 56 % to 66.6 %. All else equal, one would expect this to be associated with a reduction in the number of accidents. To determine if this was the case, the number of accidents associated with the actual use of studded tyres in the 1992-1993 (66.6 %) season was compared to a counterfactual use identical to the first season (56.0 %), while using observed values for the 1992-1993 season for all other variables than the use of studded tyres.

From the 1991-1992 season to the 1992-1993 season, use of studded tyres in the city of Stavanger increased by 10.6 percentage points. The model-estimated number of accidents in the city of Stavanger during the 1992-1993 season was 65.3. If the use of studded tyres had remained, counterfactually, at 56.0 %, the number of accident would have been 66.0. Thus, increased use of studded tyres (10.6 percentage points) was associated with an accident reduction of 1 % (65.3/66.0).

Proceeding year-by-year and city-by-city, a total of 30 data points were generated from the first study. These data points were plotted in a scatter diagram, using percentage points of change in the use of studded as abscissa, and the percent change in the number of injury accidents as ordinate. Figure 1 shows this scatter plot.

Figure 1 about here

Regression analysis was performed in order to fit an accident modification function to the data points. The number of accidents underlying each the data varies. The data points should therefore be weighted in proportion to their statistical precision. However, for the data points shown in Figure 1, a non-weighted regression was found to fit better than a weighted regression. A second-degree polynomial best fitted the data points. The quadratic term was very small and the function is nearly impossible to distinguish from a straight line. The function is consistent with a dose-response pattern in the effects of changes in the use of studded tyres.

Figure 2 shows similar data based on the second study. A total of 33 data points were identified. A second degree polynomial, estimated by means of weighted regression analysis, best fitted the data points.

Figure 2 about here

The second study contained six data points based on less than 20 percent use of studded tyres. These data points have been highlighted in Figure 2 by means of a red circle surrounding them. As can be seen, there is a tendency for the data points representing less than 20 percent use of studded tyres to show a larger increase in the number of accidents than the data points representing more than 20 percent use of studded tyres.

Data points based on both studies are shown in Figure 3. There is a total of 63 data points. A linear accident modification function was fitted to the data by means of non-weighted regression analysis. Functions based on weighted regression analyses had a poorer fit to the data than those based on non-weighted regression analyses. A second degree polynomial fitted the data marginally better than the linear function presented in Figure 3 (R-squared 0.633 versus 0.623). The polynomial function was rejected as implausible. The quadratic term was negative, implying that if there is a very large reduction in the use of studded tyres (like, say, 80 percent), a turning point is passed beyond which there is a smaller increase in the number of accidents than for smaller reductions in the use of studded tyres.

Figure 3 about here

This was regarded as implausible for two reasons. In the first place, the accident modification functions fitted separately for each of the two studies were both second degree polynomials with a positive quadratic term. A negative quadratic term was inconsistent with these functions. In the second place, the data indicate that if the use of studded tyres drops to a very low level, the increase in the number of accidents accelerates. This is indicted by the data points surrounded by red circles and yellow circles in Figure 3. These data points indicate a larger increase in the number of accidents when the use of studded tyres drops below about 25 percent than when it remains higher than this.

Both studies found, somewhat counter-intuitively, that the use of studded tyres has a larger effect on the number of accidents in non-wintry conditions than in wintry conditions. In Figure 4, the data points in Figure 3 have been divided into data points that refer to wintry weather, which means that there was either snowfall, snow lying on the ground, temperature crossing zero, or more of these conditions at the same time. Non-wintry conditions were defined as days when there was neither snowfall, nor snow on the ground nor temperature crossing zero.

Figure 4 about here

A study made in 1990 (Fosser and Ingebrigtsen 1990) found that drivers of cars with good tyres, such as new studded tyres, adapted their speed less to road surface conditions than drivers of cars with bad tyres. Cars with good tyres were driven at a higher speed on a slippery road surface than cars with bad tyres (54.2 versus 50.0 km/h). On non-slippery roads there was only a minor difference in mean speed (69.4 km/h with good tyres; 70.0 km/h with bad tyres).

5 DISCUSSION

5.1Methodological interpretations

There are, in general, two ways of interpreting research results: methodological and substantive. A methodological interpretation will normally argue for rejecting study findings, for example because they were based on poor data or flawed data analysis. Can any methodological interpretation of the findings presented above be given? At least three methodological interpretations can be imagined:

1. There is an increasingly adverse selection of drivers using studded tyres, i.e. as the group of drivers who use studded tyres becomes smaller, these drivers have a higher accident rate than other drivers.
2. The effects of studded tyres is mostly external, i.e. studded tyres influence safety mainly by wearing down snow or ice, and this effect has become smaller as the use of studded tyres has declined.
3. There have been changes over time in winter maintenance of roads. More specifically, if maintenance has been reduced, road surface conditions may have worsened, leading to more accidents.

All these hypotheses are based on the assumption that there is no true difference in accident rate between cars using studded tyres and cars using non-studded tyres. It is assumed that whatever difference one might find in the accident rate between these groups of cars is attributable to other factors, such as driver characteristics.

If there is no difference in accident rate between cars using studded tyres and cars not using studded tyres, any change in the number of accidents associated with changes in the percentage of cars using studded tyres must be attributable to other factors.

The hypothesis about adverse selection of drivers essentially states that the last drivers to quit using studded tyres are those who need them the most, because they are not highly skilled in driving on roads where studded tyres may confer a safety benefit. Simple model estimates show that if the distribution of accident rates in the population of drivers is stable, the fact that some drivers stop using studded tyres will not be associated with changes in the total number of accidents. Assuming that the differences in accident rates between different groups of drivers are attributable to driver characteristics, not to the type of tyres used, drivers who switch from one type of tyres to another will maintain their level of risk. A change in the number of accidents could only occur if drivers who quit using studded tyres experience an increase in their accident rate. But in that case, the basic assumption of no difference in accident rate between different types of tyres would be wrong, and it would be correct to say that reduced use of studded tyres causes an increase in the number of accidents.

The impact of studded tyres in wearing down snow or ice could be weakened if the percentage of cars using studded tyres is reduced. However, if the impact of studded tyres with respect to wearing down or ice has in fact been weakened as a result of less use of studded tyres, that is not really an alternative explanation of the findings, rather a specification of the causal mechanism by which studded tyres influence safety. Unfortunately, the study does not have data on the actual road surface conditions from day to day (although snowfall is an indicator). It is therefore not possible to verify if slippery road surfaces are more common today than some years ago.

The winter maintenance of roads may have changed over time. The lack of detailed information regarding winter road maintenance is clearly an omitted variable in the study. If, for example, winter road maintenance has been reduced, there is no way of knowing whether an increase in the number of accidents should be attributed to reduced use of studded tyres or a reduced standard of winter maintenance. To assess whether winter road maintenance may have been reduced, the second study extracted information on municipal costs of road maintenance from a data base maintained by Statistics Norway. Statistics regarding total operating expenditures on municipal roads and streets were selected. From 2002 to 2009, these expenditures grew by a factor of 2.29 in Oslo, 1.77 in Drammen, 1.70 in Stavanger, 1.69 in Bergen and merely 1.01 in Trondheim. The growth in road maintenance expenditures is well in excess of the general growth in wage expenditures for municipal employees in all cities except for Trondheim. It would thus appear that all cities except for Trondheim were spending more in real terms on the operation and maintenance of municipal roads in 2009 than in 2002. It was, unfortunately, not possible to distinguish between road maintenance in summer and road maintenance in winter. It can nevertheless not be ruled out that increasing the level of road maintenance may have partly counteracted the effect on accidents of reduced use of studded tyres, but the data available for this study does not permit this effect to be estimated.

5.2 Assessing the causality of the findings

To assess whether the findings of the two studies presented in this paper reflect a causal relationship between changes in the use of studded tyres and changes in the number of accidents, operational criteria applied in previous studies (Elvik 2007, 2011B) have been used. These criteria are listed in Table 6 along with an assessment of the degree to which the current study satisfies the criteria.

Table 6 about here

The first criterion states that there should be an effect, defined as statistically significant changes in the number of accidents associated with the introduction of a treatment or changes in the dose of the treatment. This criterion was not fulfilled in this study, as none of the estimated changes in the number of accidents associated with changes in the use of studded were statistically significant at conventional levels. Moreover, in the negative binomial regression models, the coefficients for the studded tyre variables did not have smaller standard errors or lower P-values than other coefficients that were estimated (criterion 2).

Two independent studies were made and their findings were highly consistent. The criterion of consistency of effects (criterion 3) is therefore fulfilled. There is little doubt about causal direction (criterion 4). In 61 out of 63 cases the direction of changes in the number of accidents (increase or decrease) were consistent with the direction of change in the use of studded tyres. The study controlled for a large number of potentially confounding variables (criterion 5); yet, in principle the possibility that an omitted variable may have influenced the results cannot be ruled out. It is, however, not obvious that changes in road maintenance should be interpreted as an omitted variable. If winter road maintenance has been increased in response to less use of studded tyres, then it forms part of the effect of changes in the use of studded tyres and should not be controlled for.

The results of the study are consistent with existing knowledge regarding the causal mechanism by which studded tyres influence safety (criterion 6). This applies both to the effects of studded tyres on the accident rates of cars using them and to changes in share of cars using studded tyres. The results of the study do not contradict theoretical notions about the effects of studded tyres and agree well with other studies (see the review of Elvik 1999 and a recent Swedish study, Strandroth et al. 2012) (criterion 7). A clear dose-response pattern was found (criterion 8). As for the specificity of effect (criterion 9), a somewhat counter-intuitive pattern was found, as studded tyres appear to have a larger effect on accidents during non-wintry conditions, than during wintry conditions, i.e. days when there is either snowfall, snow lying on the ground, temperature crossing zero degrees Celsius or all these conditions obtain. This pattern is likely to be attributable to differences in speed adaptation between drivers using studded tyres and drivers not using studded tyres.

6 CONCLUSIONS

The main conclusions of the studies reported in this paper can be summarised as follows:

1. Reduced use of studded tyres in major Norwegian cities is associated with an increase in the number of injury accidents during the season when the use of studded tyres is permitted.
2. Increased use of studded tyres in major Norwegian cities is associated with a reduction in the number of injury accidents during the season when the use of studded tyres is permitted.

3. The association between changes in the use of studded tyres and changes in the number of accidents is highly consistent and can be described in terms of an accident modification function.
4. There are indications that when the use of studded tyres drops below about 20-25 percent of cars, there is a larger increase in the number of accidents than when the use of studded tyres stays above this level.
5. There are stronger reasons for believing that the associations found in this study are causal than for believing the opposite (i.e. that they are the result of bias, chance or confounding).
6. The study was not able to obtain data regarding winter maintenance of roads. The possibility that changes in winter maintenance of roads have influenced the number of accidents cannot be ruled out.

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LIST OF TABLES AND FIGURES

Table 1:

Variables included in the two studies

Table 2:

Peak use of studded tyres in each city by season. Percent of cars using studded tyres by city

Table 3:

Coefficients estimated in model of factors influencing the use of studded tyres

Table 4:

Coefficients estimated by means of negative binomial regression in the first study (Fridstrøm 2000)

Table 5:

Coefficients estimated by means of negative binomial regression in the second study (Elvik and Kaminska 2011)

Table 6:

Assessing study findings in terms of criteria of causality

Figure 1:

Accident modification function for changes in the share of cars using studded tyres based on the first study (Fridstrøm 2000)

Figure 2:

Accident modification function for changes in the share of cars using studded tyres based on the second study (Elvik and Kaminska 2011)

Figure 3:

Accident modification function for changes in the share of cars using studded tyres based on the both studies (Fridstrøm 2000, Elvik and Kaminska 2011)

Figure 4:

Changes in the number of injury accidents associated with changes in the use of studded tyres during wintry and non-wintry conditions

Table 1:

Category	Name of variable	Unit of measurement
Dependent		
D1	Police reported injury accidents	Number per day
D2	Insurance reported accidents	Estimated number per day
Independent		
I1	Estimated percentage using studded tyres	Percent of vehicles
I2	Season when use of studded tyres is allowed	Dummy = 1 in season
Confounding		
C1	Traffic volume	Automatic count per day
C2	Year	2002, 2003, etc
C3	Years elapsed since January 1, 2002	Decimal count (1/365, 2/365 ...)
C4	Sundays and public holidays	Dummy
C5	Saturdays	Dummy
C6	Easter	Dummy (8 days)
C7	Ascension day	Dummy (4 days)
C8	Whitsun	Dummy (5 days)
C9	Christmas	Dummy (10 days)
C10	Length of daylight	Sinus curve; share of 24 hours
C11	Minimum temperature	Degrees Celcius
C12	Maximum temperature	Degrees Celcius
C13	Days with temperature consistently below zero	Dummy
C14	Days with temperature consistently above zero	Dummy
C15	Days with temperature crossing zero	Dummy
C16	Precipitation as rain	Millimetres
C17	Precipitation as snow	Millimetres
C18	Snow depth	Estimated in centimetres
C19	First snow	Date of first snow (dummy)
C20	Last snow	Date of last snow (dummy)
C21	City identifier for Oslo	Dummy
C22	City identifier for Drammen	Dummy
C23	City identifier for Stavanger	Dummy
C24	City identifier for Bergen	Dummy
C25	City identifier for Trondheim	Dummy
Mediating		
M1	Mean speed of traffic per city per day	Kilometres per hour
Other		
O1	Fee for use of studded tyres	Dummy

Table 2:

	Peak percentage of cars using studded tyres in each city				
Season	**Oslo**	**Drammen**	**Stavanger**	**Bergen**	**Trondheim**
1990-1991	—	—	—	78.5	—
1991-1992	—	—	56.0	78.1	—
1992-1993 (#)	85.1	—	66.6	78.3	90.9
1993-1994	80.1	—	76.1	73.3	98.7
1994-1995	83.7	—	73.7	76.8	89.0
1995-1996	81.2	—	75.6	73.7	—
1996-1997	75.3	—	70.8	63.0	78.1
1997-1998	63.3	—	63.8	53.1	72.9
1998-1999	53.7	—	43.1	45.9	67.5
1999-2000	35.6	—	41.9	36.2	66.9
2002 (ψ)	32.0	40.1	28.8	31.1	44.5
2002-2003	28.4	41.3	29.1	32.4	41.1
2003-2004	28.0	33.7	27.8	26.8	39.5
2004-2005	23.8	29.4	29.7	29.9	37.7
2005-2006	19.3	25.3	30.8	27.8	34.9
2006-2007	19.5	26.2	27.6	21.2	30.4
2007-2008	16.2	26.6	33.4	9.9	20.5
2008-2009	16.5	30.5	27.8	14.0	20.4

— = Data are not available

(#) From January 1, 1993 in Oslo

(Ψ) From January 1, 2002 in all cities

Table 3:

Variable	Coefficient	Standard error	P-value
Constant term	1647.362	44.803	0.000
Year	-0.822	0.022	0.000
Dummy for Oslo	Omitted		
Dummy for Drammen	2.492	0.169	0.000
Dummy for Stavanger	1.002	0.156	0.000
Dummy for Bergen	-0.440	0.149	0.003
Dummy for Trondheim	5.661	0.150	0.000
Seasonal dummy	26.792	0.122	0.000
Dummy for tax	-4.042	0.175	0.000
R-squared	0.845		

Table 4:

Variable	Coefficient	Standard error	P-value
Snowfall (-1/√(mms as melted + 0.1)	0.119	0.066	0.073
Snowdepth (-1/√(cms + 1)	-0.482	0.215	0.024
Cross zero (temperature crosses freezing point)	-0.116	0.058	0.046
Rainfall (-1/(mms + 0.5)	0.087	0.011	0.000
Snowfall · ln(percent studded tyres + 1)	-0.001	0.016	0.955
Snowdepth · ln(percent studded tyres + 1)	0.097	0.051	0.058
Cross zero · ln(percent studded tyres +1)	0.041	0.015	0.008
Ln(traffic volume) (fixed at 1.000)	1.000		
Dummy for Oslo	-10.816	0.071	0.000
Dummy for Stavanger	-10.090	0.074	0.000
Dummy for Bergen	-8.661	0.069	0.000
Dummy for Trondheim (set to zero)	-10.545	0.074	0.000
Sinus curve for daylight in Oslo	0.041	0.024	0.083
Sinus curve for daylight in Bergen	0.110	0.029	0.000
Sinus curve for daylight in Trondheim	0.200	0.044	0.000
Sinus curve for daylight in Stavanger	0.123	0.041	0.003
Dummy for Sundays and holidays	-0.121	0.028	0.000
Dummy for Saturdays	0.044	0.026	0.094
Dummy for Easter	-0.021	0.073	0.774
Dummy for Ascension day	-0.119	0.098	0.225
Dummy for Whitsun	0.215	0.078	0.006
Dummy for Christmas	-0.274	0.079	0.001
Year count	-0.030	0.004	0.000
Over-dispersion parameter	0.056		
Elvik index of goodness of fit	0.936		
Number of observations	11359		

Table 5:

Variable	Coefficient	Standard error	P-value
Constant term	-5.347	0.692	0.000
Snowfall (-1/√(mms as melted + 0.1)	0.023	0.116	0.841
Snowdepth (-1/√(cms + 1)	-0.338	0.366	0.355
Cross zero (temperature crosses freezing point)	-0.044	0.073	0.550
Rainfall (-1/(mms + 0.5)	0.044	0.012	0.000
First snow (dummy = 1 on day of first snow)	0.243	0.169	0.151
Last snow (dummy = 1 on day of last snow)	-0.134	0.209	0.521
Snowfall · ln(percent studded tyres + 1)	0.020	0.036	0.582
Snowdepth · ln(percent studded tyres + 1)	0.034	0.114	0.768
Cross zero · ln(percent studded tyres +1)	0.030	0.025	0.229
Ln(traffic volume)	0.470	0.064	0.000
Dummy for Oslo	1.297	0.036	0.000
Dummy for Drammen	-1.397	0.066	0.000
Dummy for Stavanger	0.416	0.084	0.000
Dummy for Bergen	1.346	0.114	0.000
Dummy for Trondheim (set to zero)	0.000		
Share of daylight (proportion of 24 hours)	-0.294	0.082	0.000
Dummy for Sundays and holidays	-0.290	0.040	0.000
Dummy for Saturdays	-0.214	0.035	0.000
Dummy for Easter	-0.199	0.074	0.007
Dummy for Ascension day	0.082	0.074	0.271
Dummy for Whitsun	0.079	0.100	0.433
Dummy for Christmas	-0.384	0.083	0.000
Year count	-0.019	0.004	0.000
Over-dispersion parameter	0.075	0.011	0.000
Elvik index of goodness of fit	0.919		
Number of observations	13269		

Table 6:

Criterion of causality	Operational definition	Fulfilment in this study
1. Statistical association	A statistically significant change in the number of accidents associated with changes in the use of studded tyres	Not fulfilled; the changes in the number of accidents associated with changed use of studded tyres were not statistically significant
2. Strength of association	Comparison of the P-values of the coefficients estimated in the negative binomial regression model	Not fulfilled; most coefficients had lower P-values than those referring to studded tyres
3. Consistency of association	The consistency in direction and size of effect attributed to safety treatment across subsets of the data, different model specifications, or repeated, independent studies	Two independent studies were made and the findings of the two studies were highly consistent
4. Clear causal direction	The temporal order between variables; a priori considerations; reversal of effect when treatment is removed	Of a total of 63 data points, 61 were consistent with a clear direction of causality (more use of studded tyres = fewer accidents; less use of studded tyres = more accidents)
5. Control for confounders	The identification of potentially confounding variables; existence of an effect attributed to treatment after potentially confounding variables have been controlled for; completeness of the control for confounding variables	The two studies controlled for more than 20 potentially confounding variables; effects attributed to changes in the use of studded tyres remained highly consistent. Whether important variables have been omitted is debatable
6. Causal mechanism	Changes in target risk factors influenced by a road safety treatment and changes in risk factors representing behavioural adaptation to the treatment	The results are consistent with the causal mechanisms for studded tyres, i.e. (1) improved friction for cars using such tyres, and (2) faster removal of snow and ice from the road surface when the use of studded tyres is high than when it is low
7. Theoretical explanation	Findings should not contradict well established laws of physics or laws of human perception and information processing	The findings are consistent with controlled trials comparing stopping distance with different types of tyres and previous evaluation studies
8. Dose-response pattern	Treatments that are intense or have large effects on target risk factors should be associated with larger changes in safety than less intense treatments or treatments with small effects on target risk factors	There is a very clear and consistent dose-response pattern. The pattern found in the first study was reproduced in the second study
9. Specificity of effect	An effect of safety treatments targeted at clearly defined groups should only be found in those groups and not in other groups	This criterion is only partly satisfied; effects were larger in non-wintry conditions than in wintry conditions, but there was an effect in both conditions

Figure 1:

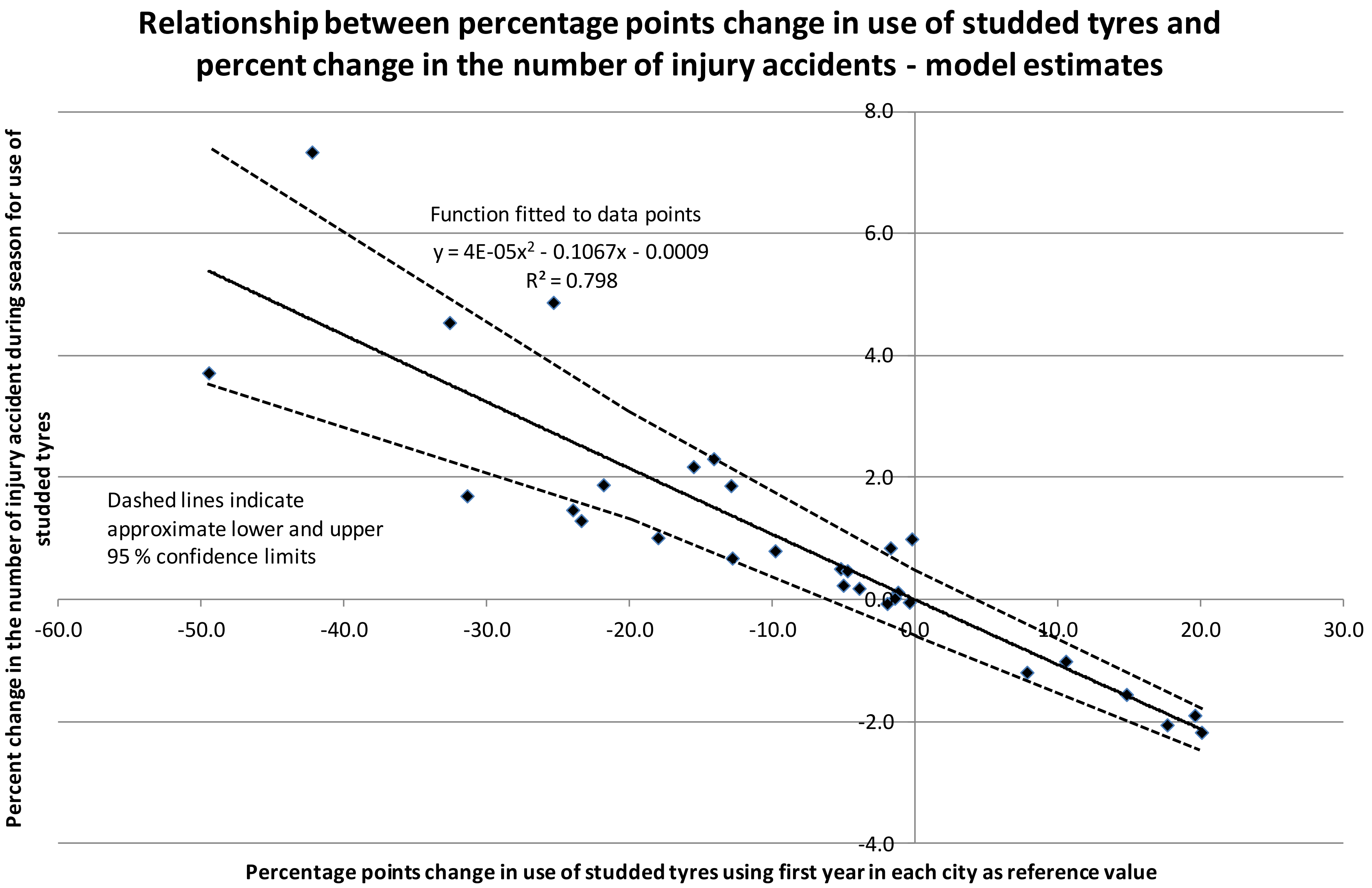
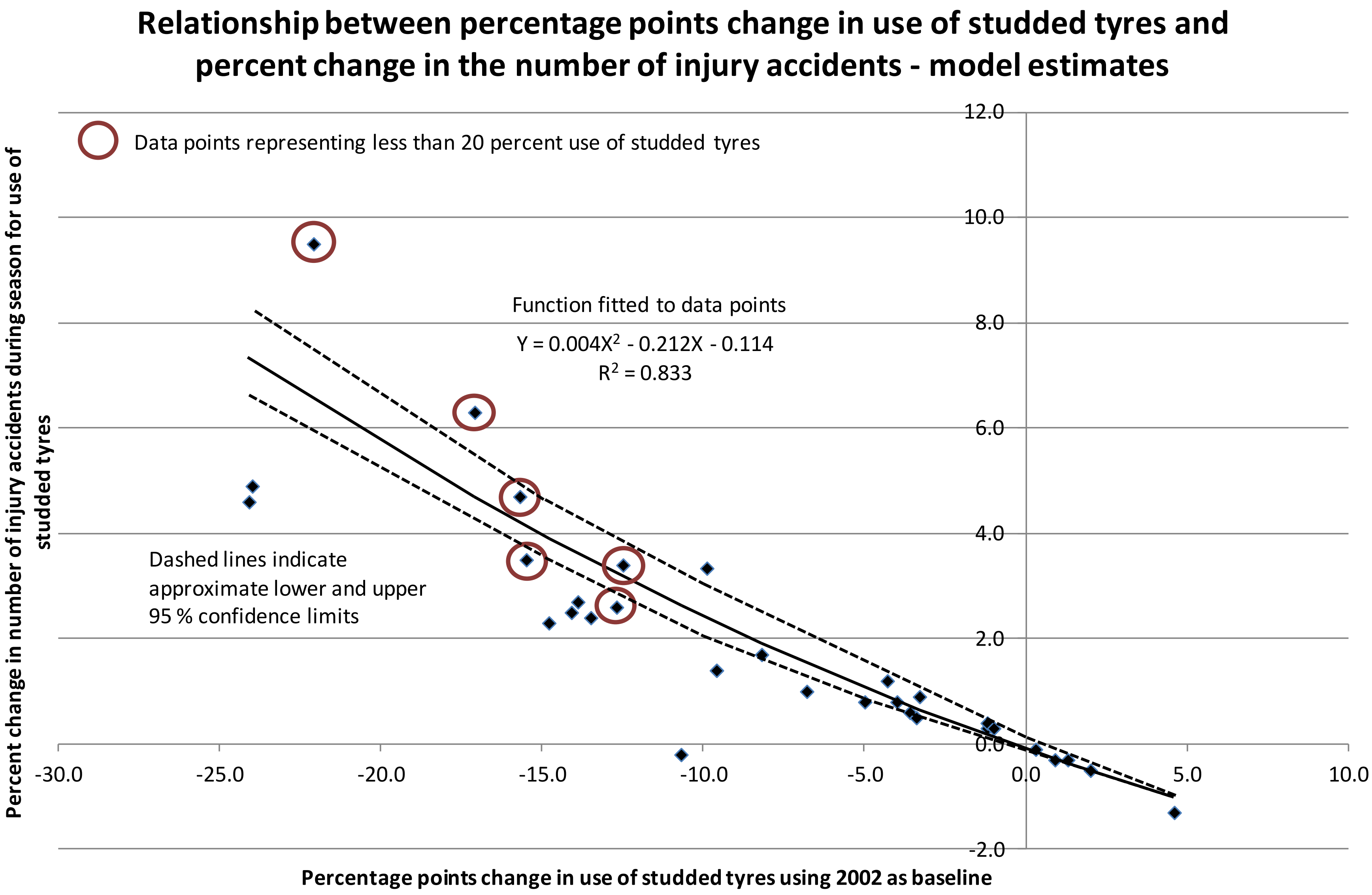
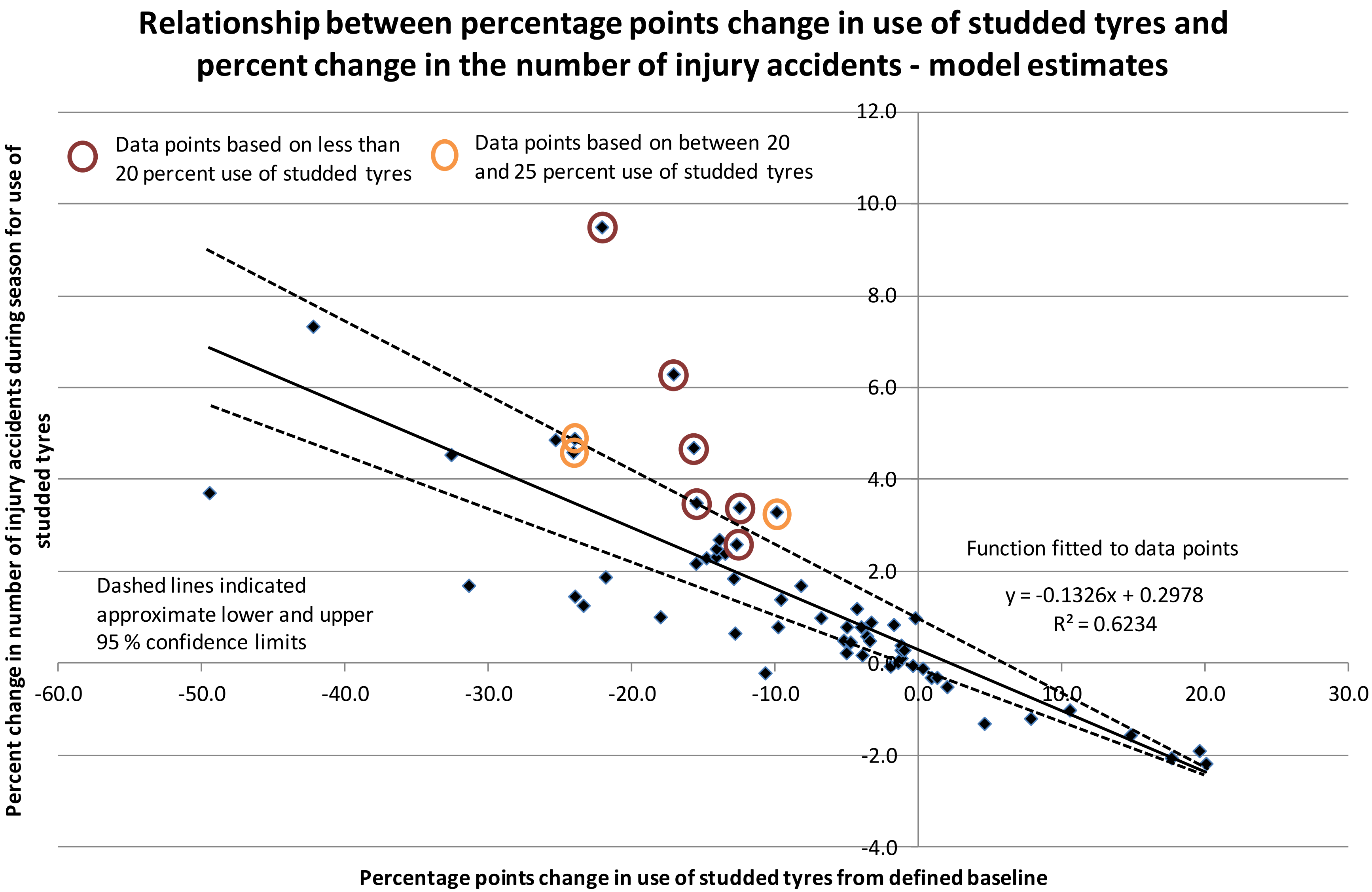

Relationship between percentage points change in use of studded tyres and percent change in the number of injury accidents - model estimates
Function fitted to data points
y = 4E-05x² - 0.1067x - 0.0009
R² = 0.798
Dashed lines indicate approximate lower and upper 95 % confidence limits
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-60.0
-50.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
Percent change in the number of injury accident during season for use of studded tyres
Percentage points change in use of studded tyres using first year in each city as reference value

Figure 2:



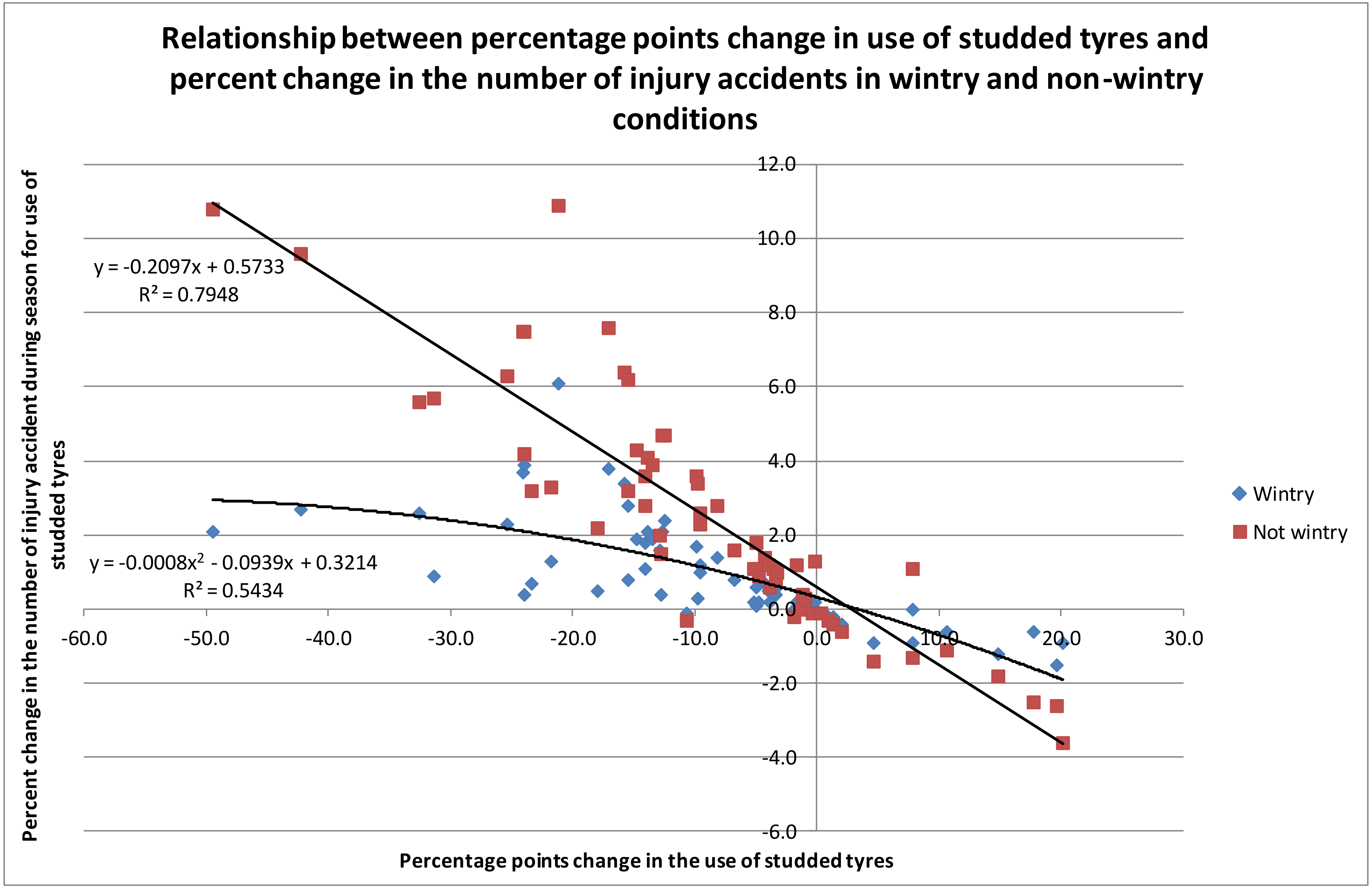
Relationship between percentage points change in use of studded tyres and percent change in the number of injury accidents - model estimates
Data points representing less than 20 percent use of studded tyres
Function fitted to data points
Y = 0.004X2 - 0.212X - 0.114
R2 = 0.833
Dashed lines indicate approximate lower and upper 95 % confidence limits
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
Percent change in number of injury accidents during season for use of studded tyres
Percentage points change in use of studded tyres using 2002 as baseline

Figure 3:



Relationship between percentage points change in use of studded tyres and percent change in the number of injury accidents - model estimates
Data points based on less than 20 percent use of studded tyres
Data points based on between 20 and 25 percent use of studded tyres
Dashed lines indicated approximate lower and upper 95 % confidence limits
Function fitted to data points
y = -0.1326x + 0.2978
R² = 0.6234
Percent change in number of injury accidents during season for use of studded tyres
Percentage points change in use of studded tyres from defined baseline
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-60.0
-50.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0

Figure 4:



Relationship between percentage points change in use of studded tyres and percent change in the number of injury accidents in wintry and non-wintry conditions
Percent change in the number of injury accident during season for use of studded tyres
Percentage points change in the use of studded tyres
y = -0.2097x + 0.5733
R² = 0.7948
y = -0.0008x² - 0.0939x + 0.3214
R² = 0.5434
Wintry
Not wintry
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-60.0
-50.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0

APPENDIX 1: ILLUSTRATION OF HOW TO INTERPRET MODEL COEFFICIENTS REFERRING TO THE USE OF STUDDED TYRES

Two the three coefficients referring to the use of studded tyres were positive in the first; all three were positive in the second study. It is therefore not immediately obvious how a reduced use of studded tyres is associated with an increased number of accidents. The signs of the coefficients might suggest that the opposite is the case. This appendix therefore contains an explanation of how to interpret these coefficients and how, despite their positive signs, they actually predict that a reduced use of studded tyres is associated with an increased number of accidents.

The coefficients estimated in the first study will be used as illustration. To illustrate the interpretation of the coefficients Table A.1 has been developed.

The first column shows the proportion using studded tyres. A range from zero to 90 percent has been applied. The next column shows the values of ln(studuse + 1). For a proportion of 0.1, this equals ln(1.1) = 0.095. The third column is the transformed variable for a snowfall of 5 centimetres, which is (sqr = square root):

Snowfall = –1/sqr(5 + 0.1) = –1/2.258 = –0.443.

The fourth column presents the transformed snowdepth variable, assuming a snowdepth of zero:

Snowdepth = –1/sqr(0 + 1) = –1/1 = –1.

The fifth column is the dummy for cross-zero, which in the upper half of the Table is assumed to take on the value of 1, in the lower half of the Table the value of zero.

The next columns (6, 7, 8) contain the interaction terms between the use of studded tyres and the three weather variables, i.e. studuse * snowfall, studuse * snowdepth and studuse * crosszero. Thus for a use of studded tyres of 10 percent, the interaction terms become, respectively, 0.095 * –0.443 = –0.042; 0.095 * –1 = –0.095; 0.095 * 1 = 0.095.

These interaction terms are then multiplied by the relevant coefficients (columns 9, 10, 11). The coefficients are –0.001 for the studuse * snowfall interaction, 0.097 for the studuse * snowdepth interaction and 0.041 for the studuse * crosszero interaction. Taking the exponential function of the sum of the products of the coefficients and interaction terms gives an estimate of the relative number of accidents (column 12). When the use of studded tyres is zero, the relative number of accidents equals 1.000. As the use of studded tyres in wintry conditions increases to 90 percent, the estimated relative number of accidents declines to 0.965. Conversely, a reduction in the use of studded tyres from, say 80 percent to 40 percent would be associated with an increase in the number of accidents of 0.981/0.968 = 1.013 = 1.3 percent on days when is a snowfall of 5 centimetres.

The lower half of Table A.1 refers to a day without wintry conditions; i.e. there is no snowfall, zero snowdepth and the temperature does not cross the freezing point. All calculations are identical to those in the upper half of the table, except for the fact that the winter condition variables assume different values (snowdepth is equal to zero in both sections of the table)

As can be seen from the rightmost column, the effects of studded tyres when conditions are not wintry are greater than during wintry conditions. For non-wintry conditions, reducing the use of studded tyres from 80 percent to 40 percent would be associated with an increase of 2.4 percent in the number of accidents – almost twice the value found for wintry conditions. These findings were confirmed for the second study, although the coefficients applying to studded tyres had different values than in the first study.

Table A.1: Estimate of effect on accidents of reduced use of studded tyres

(1)	(2)	(3)	(4)	(5)	(6) = (2)*(3)	(7) = (2)*(4)	(8) = (2)*(5)	(9)	(10)	(11)	(12)
Studuse	Ln(stud+1)	Snow	Depth	Frost	Stud*snow	Stud*depth	Stud*frost	Coeff*(6)	Coeff*(7)	Coeff*(8)	Exp(9+10+11)
This part of the table refers to a random day with 5 centimetres of snowfall, zero snowdepth and temperature crossing zero (wintry conditions)											
0.0	0.000	-0.443	-1.000	1	0.000	0.000	0.000	0.00000	0.00000	0.00000	1.000
0.1	0.095	-0.443	-1.000	1	-0.042	-0.095	0.095	0.00004	-0.00925	0.00391	0.995
0.2	0.182	-0.443	-1.000	1	-0.081	-0.182	0.182	0.00008	-0.01769	0.00748	0.990
0.3	0.262	-0.443	-1.000	1	-0.116	-0.262	0.262	0.00012	-0.02545	0.01076	0.986
0.4	0.336	-0.443	-1.000	1	-0.149	-0.336	0.336	0.00015	-0.03264	0.01380	0.981
0.5	0.405	-0.443	-1.000	1	-0.180	-0.405	0.405	0.00018	-0.03933	0.01662	0.978
0.6	0.470	-0.443	-1.000	1	-0.208	-0.470	0.470	0.00021	-0.04559	0.01927	0.974
0.7	0.531	-0.443	-1.000	1	-0.235	-0.531	0.531	0.00023	-0.05147	0.02176	0.971
0.8	0.588	-0.443	-1.000	1	-0.260	-0.588	0.588	0.00026	-0.05702	0.02410	0.968
0.9	0.642	-0.443	-1.000	1	-0.284	-0.642	0.642	0.00028	-0.06226	0.02632	0.965
This part of the table refers to a random day with no snowfall, zero snowdepth and no crossing of zero degrees (not wintry conditions)											
0.0	0.000	-3.162	-1.000	0	0.000	0.000	0.000	0.00000	0.00000	0.00000	1.000
0.1	0.095	-3.162	-1.000	0	-0.301	-0.095	0.000	0.00030	-0.00925	0.00000	0.991
0.2	0.182	-3.162	-1.000	0	-0.577	-0.182	0.000	0.00058	-0.01769	0.00000	0.983
0.3	0.262	-3.162	-1.000	0	-0.830	-0.262	0.000	0.00083	-0.02545	0.00000	0.976
0.4	0.336	-3.162	-1.000	0	-1.064	-0.336	0.000	0.00106	-0.03264	0.00000	0.969
0.5	0.405	-3.162	-1.000	0	-1.282	-0.405	0.000	0.00128	-0.03933	0.00000	0.963
0.6	0.470	-3.162	-1.000	0	-1.486	-0.470	0.000	0.00149	-0.04559	0.00000	0.957
0.7	0.531	-3.162	-1.000	0	-1.678	-0.531	0.000	0.00168	-0.05147	0.00000	0.951
0.8	0.588	-3.162	-1.000	0	-1.859	-0.588	0.000	0.00186	-0.05702	0.00000	0.946
0.9	0.642	-3.162	-1.000	0	-2.030	-0.642	0.000	0.00203	-0.06226	0.00000	0.942