TØI report 493/2000
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Oslo 2000, 40 pages Norwegian language

Summary:

The safety effect of studded tyres in Norwegian cities

Background and aim of study

The use of studded tyres in winter has been widespread in Norway since the 1970's. Such tyres are generally believed to provide a better grip on snowy and icy road surfaces and hence to enhance accessibility as well as safety. Indeed, well controlled scientific studies do suggest that studded tyres serve to reduce the accident risk, although the effect is relatively small, probably of the order of 4 per cent, when aggregated over the entire winter season (Elvik 1999, Fosser and Sætermo 1995).

In recent years, rising concerns have been voiced about the *disadvantages* of studded tyre use, which include excessive *damage to the road surface*, and hence sharply increased costs of maintenance, as well as the generation of *air borne particles* from the road surface, which, when inhaled, represent a health threat. A third inconvenience is the *dust and dirt* deposits from these particles, and a fourth is the additional *noise* generated by studded tyres on snow-free surfaces. Finally, one should take into consideration that studded tyres provide *less friction on a clear dry road* than do ordinary winter (or summer) tyres.

These concerns appear especially important in the cities, where, in spite of occasional snowfalls, the main streets remain clear for the better part of the season, owing to the winter maintenance effort undertaken by the public roads authorities, to the (upward) variations in temperature, and to the fact that motorists gradually wear down the snowy surface as they drive on it. Thus, it is felt that, at least in the cities, the advantages of studded tyre use may not outweigh the inconveniences.

For these reasons, the Norwegian public roads authorities have for some years advocated a reduction in the rate of studded tyre use. Since the mid nineteen nineties, this rate has therefore been dropping in all of the four major urban areas – Oslo, Bergen, Trondheim and Stavanger.

Since December 1999, the city of Oslo has been taxing the use of studded tyres, at a rate of NOK 1000 for the entire season, or NOK 25 per day (€ 1 = appr NOK 8). The aim is to bring the rate of studded tyre use down to 20 per cent of all private cars. In February 2000, the estimated rate in Oslo was 35 per cent.

The *studded tyre season*, i e the general period allowed for studded tyres use in (southern and central) Norway, ranges from November 1 until the first weekend after Easter.

In order to judge whether this policy directed towards reduced studded tyre use has a cost in terms of unacceptably increased accident rates, we have analyzed the daily accident counts recorded in Oslo, Bergen, Trondheim and Stavanger over a period of almost 10 years.

Data

Injury accident counts by date of occurrence have been extracted from the so-called STRAKS register of the Public Roads Administration. These data cover the period until March 31, 2000, i e almost to the end of the studded tyre season 1999-2000.

Road accident records from all the major insurance companies of Norway are gathered in the so-called TRAST register. From this source, we have extracted data on *property damage only (PDO) acccidents* as well as on injury accidents. Certain accident types deemed to be immaterial in relation to our objective were excluded from the counts; these include accidents occurring when backing up, collisions with parked vehicles, and accidents of unknown type.

The unit of observation in the TRAST register is the accident report (insurance claim). In accidents between two insurance policy holders, there will normally be two reports. To correct for this, we have weighed together the accident records by attaching a weight of one half to all cases where the counterpart is a motor vehicle, and a weight of one to the cases without a counterpart or when the counterpart is a pedestrian, bicyclist, animal, tramway, train, or fixed private property. The resulting weighted sum is, if necessary, rounded up to the nearest integer.

The TRAST register is generally updated only once a year. Hence from this source we have not been able to obtain data extending beyond December 31, 1999.

Our third major source of data is the Norwegian Meteorological Institute, from which we have obtained daily *weather records* for each of the four cities, covering the period from January 1, 1990 until March 31, 2000. The following indicators are given: precipitation in the form of snow, rain or mixed, current level of snow depth, and minimum and maximum temperature.

Our fourth source is the collection of *traffic counts* made by the Public Roads Administration or, in the case of Oslo, by the cordon toll ring company. These counts provide, in principle, records on daily traffic flows at designated points. A single counting station is used in each of the three smaller cities, while in Oslo we add together the flows through all of the 19 toll plazas. The idea is to keep track, at least roughly, of the day-to-day variations in accident *exposure*.

The time series obtained from the counting stations are generally not complete, owing to occasional mechanical breakdown etc. Thus, a certain amount of observations (appr 20 per cent) are lost due holes in the time series.

Many counting stations also provide speed measurements, although here the rate of mechanical or other failure is much higher. For the cities of Bergen, Trondheim and Stavanger we have, however, been able to compile time series on *mean daily speed* at one counting station, covering around 62 per cent of the dates between May 1, 1990 and December 31, 1999. Here, the idea is to be able to check whether speed varies significantly with the weather conditions, something which might help understand the effects on accident rates of wintry weather and/or of studded tyres.

A sixth source of data is the *calendar*. Certain events tend to inflate or deflate the traffic volume, or at least to affect the representativity of a given counting point. Thus, we keep track of major holidays and of Saturdays and Sundays versus ordinary weekdays. Also, we calculate a linear trend term defined as the amount of time elapsed since December 31, 1989.

Our final and most important set of sources relates to the principal independent variable of interest – the rate of *studded tyre use*.

Annual sample surveys have been made at mid winter (late January/early February) since the early 1990s in all of the four major cities. These surveys are believed to provide fairly good estimates of the *maximum rate of use* over the winter.

However, to apply this information to an analysis based on daily data, one must impute a relationship describing how the rate of use rises to this seasonal maximum and how it eventually falls back to zero.

In this context, there are two accessory sources of data that come in handy. One is the set of surveys made by Fosser (1992, 1994), from which we have been able to estimate the mean use of studded tyres each month during the 1991-92 and 1993-94 seasons, in each city. The other source is the set of surveys made by ViaNova (1998, 1999) in Oslo, from which one can derive estimates on the rate of use at certain, exact dates.

To summarize and exploit the information contained in these three separate sources, we fitted a logistic regression model explaining the rate of use at a given date as a function of (i) the time lapse since the start of the studded tyre season, (ii) the remaining time until its end, (iii) the accumulated number of frost days (i e, days with a minimum temperature below 0°C) since the end of summer, (iv) whether or not the season’s first snowfall has taken place, (v) the mean level of snow depth over the last 30 days, (vi) a dummy correcting for changes in the studded tyre survey sampling method, and (viii) the log-odds of studded tyres use according to the main mid winter measurements.

The idea of including the last variable as an independent one is to force the curve through our most reliable points of observation. For the same reason, these observations were given a five times higher weight in the estimation compared to the data from our accessory sources.

The imputed daily time series on studded tyre use are shown in Figure 1, in which the data have been sorted, first by (ascending size of the) city, and then chronologically.

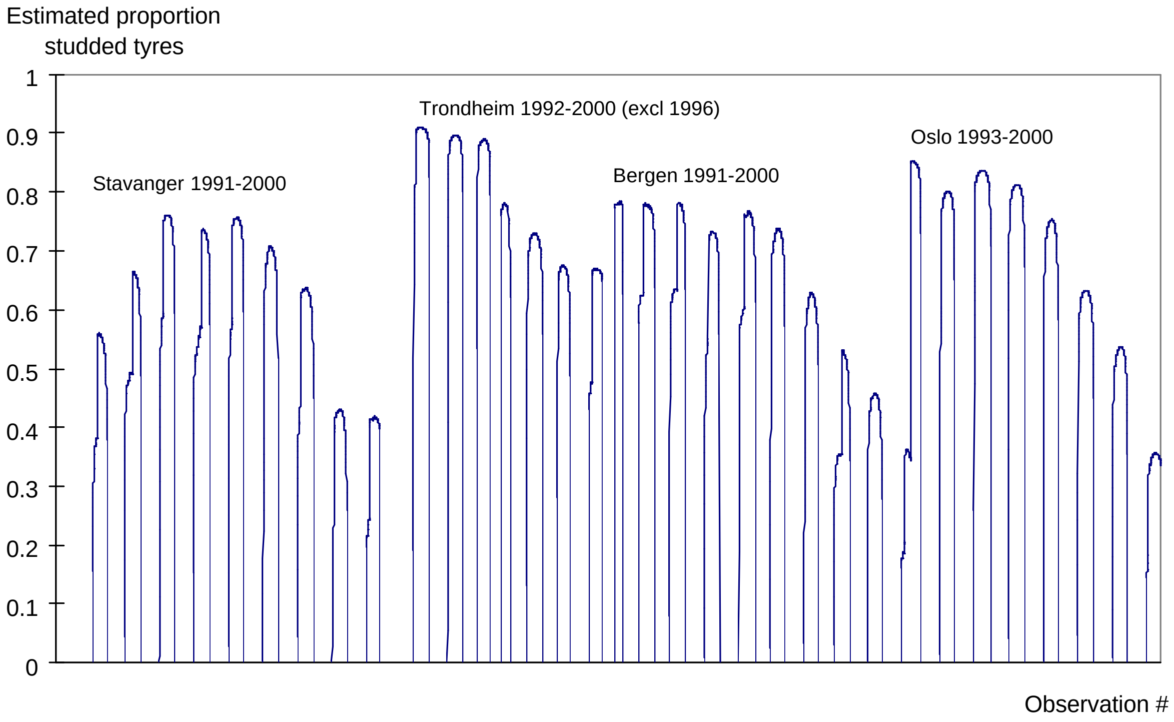

Figure 1: Estimated studded tyre use in the four largest Norwegian cities

One notes that for more than half the sample observations, the rate of studded tyre use is zero. This so because data are included for the entire summer season as well, as a «control group» against which the effect of wintry weather and studded tyres will be judged.

To exploit the information contained in all of these different data sources, covering somewhat different time spans, we constructed three more or less overlapping samples.

Sample I merges data from the STRAKS register of injury accidents with traffic count data, weather records, calendar data, and imputed studded tyre use. This sample, which totals 11 436 units of observations, is the only one covering the (almost entire) studded tyre season 1999-2000.

Sample II is somewhat smaller than Sample I, as it is limited by the availability of insurance accident records. Thus, this sample includes data on PDO accidents as well as on injury accidents during 1992-1999. It holds 10 316 observations .

Sample III is the intersection of observations on injury accidents, PDO accidents, traffic counts and *speed* measurements. This sample contains 5 387 observations, but none from Oslo.

Method

Accident counts are analysed by means of negative binomial (i e, generalized Poisson) regression analysis, performed by means of the LIMDEP computer software.

The accident count model is essentially log-linear, i e the log of the expected number of accidents on day t in city r (w^{rt}, say) is modelled as a linear function of a set of coefficients:

$$w^{rt} = e^{\sum_j b_j x_j^{rt}} \qquad (1)$$

The independent variables x_j^{rt} need, however, not be linear functions; they could be non-linear transformations of certain indicators of interest. Thus, in general we assume weather variables to have clearly decreasing marginal effects, e g

$$\begin{aligned} x_1^{rt} &= -\frac{1}{\sqrt{\frac{7}{24}v_1^{rt} + \frac{17}{24}v_1^{r,t+1} + a_1}}, \\ x_2^{rt} &= -\frac{1}{\sqrt{v_2^{rt} + a_2}}, \\ x_3^{rt} &= v_3^{rt} \\ x_4^{rt} &= -\frac{1}{v_4^{r,t+1} + a_4} \end{aligned} \qquad (2)$$

where v_1^{rt} is the amount of *precipitation in the form of snow* recorded on day t in city r, v_2^{rt} is the *accumulated snowfall over the previous 10 days* (limited by the current level of snow depth), v_3^{rt} is a dummy for *frost* (equal to one if the temperature drops below 0°C during the day), and v_4^{rt} is the amount of *rain or mixed precipitation*. Since precipitation is generally recorded every day at 7 a m, we count, as «today's» snowfall, 7/24 of the snowfall recorded at 7 a m the same day, and 17/24 of the snowfall recorded the next morning. When it comes to rainfall, however, we consider the precipitation arriving between midnight and 7 a m as more or less irrelevant in relation to the traffic, and use only the next day's recording.

The functional forms used in equations (2) where decided upon following certain trial-and-error, best-fit likelihood ratio tests. The same applies to the constants a_i, which are necessary in order to avoid division by zero.

The *percentage rate of studded tyre use* (p^{rt}, say) essentially enters the model through certain interactions terms defined in relation to the weather variables, e g

$$x_{i+4}^{rt} = x_i^{rt} \cdot ln\left(p^{rt} + 1\right), \quad i = 1,2,3,4 \qquad (3)$$

By this specification[1], we attempt to avoid or minimise omitted variable bias due to the possible correlation between studded tyre use and any variable exhibiting a

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[1] The accident model does not include any direct term $ln(p+1)$. When this term is entered into the model, it proves insignificant. The same applies to the interaction between rainfall and studded tyre use.

clear seasonal pattern of variation (confer Figure 1). Only variables that also work in interaction with the weather factors are likely to give rise to such bias.

In addition to our main independent variable of interest (weather and studded tyre use), the accident count model includes, as control variables, a dummy for each of the four cities, a sinus curve – with coefficients differing between the cities – designed to capture variations in daylight[2], a set of calendar event dummies, a linear trend term (time since Dec 31, 1989, measured in years or in decimal parts thereof), and a logarithmic measure of the traffic count, our proxy for exposure.

With this specification, we estimate one equation explaining *injury accident* counts based on Sample I, and one equation for *insurance accident* counts (including PDO as well as injury accidents) based on Sample II.

In addition, we estimate, based on Sample III, a linear, ordinary least squares regression model explaining *mean daily speed*. Here, the independent variables are essentially the same as in the accident count models, However, the best-fit functional forms of the weather variables are different:

$$\begin{aligned} x_1^{rt} &= \frac{7}{24} v_1^{rt} + \frac{17}{24} v_1^{r,t+1}, \\ x_2^{rt} &= \sqrt{v_2^{rt}}, \\ x_3^{rt} &= v_3^{rt}, \\ x_4^{rt} &= \sqrt{v_4^{r,t+1}}. \end{aligned} \tag{4}$$

Thus, the mean daily speed is a linear function of today's snowfall, but a square root function of previous, accumulated snowfall and of today's rainfall.

Results

Estimation results for injury and insurance accidents, respectively, are shown in Table 1.

The exposure term comes out with a coefficient not significantly different from one in the injury accident model. It has hence been constrained to one in a second round of estimation. This implies that the coefficients have interpretations, not only as marginal effects on the expected number of accidents, but also as effects on risk.

To interpret our main effects of interest – those of weather conditions and their interaction with studded tyre use – it is useful to draw a few diagrams, showing the implied partial relationship between the expected number of accidents and one or two independent variables.

Thus, in Figure 2 we depict the relationship between *injury* accident frequency and *today's snowfall*. Figure 3 is an analogous graph drawn with respect to the

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[2] The curve equals –1 at summer solstice, 0 at equinox, and +1 at winter solstice. Thus, the curve correlates positively with the length of the night rather than with the amount of daylight.

accumulated amount of snowfall over the last 10 days (limited, though, by the current level of snow depth)[3].

Table 1: Estimation results in negative binomial regression models for accident counts.

Independent variable	Injury accidents		Insurance accidents	
	Coefficient	t-value	Coefficient	t-value
X1: today's snowfall: -1/√ (mms as melted + 0.1)	0.119	1.80	0.208	6.61
X2: 10 days' accumul'd snow depth: -1/√(cms +1)	-0.482	-2.25	0.210	2.06
X3: frost	-0.116	-1.99	0.005	0.16
X4: today's rainfall: -1/(mms + 0.5)	0.087	7.69	0.135	23.39
X5: X1 × log(per cent studded tyres +1)	-0.001	-0.06	-0.001	-0.08
X6: X2 × log(per cent studded tyres +1)	0.097	1.89	0.041	1.70
X7: X3 × log(per cent studded tyres +1)	0.041	2.66	0.040	5.45
Exposure (traffic count)	1.000	-	0.653	27.49
Oslo dummy	-10.816	-152.15	-3.637	-12.42
Bergen dummy	-8.661	-125.11	-2.395	-11.04
Trondheim dummy	-10.545	-143.24	-3.984	-15.96
Stavanger dummy	-10.090	-136.02	-3.373	-14.77
Sinus curve for daylight in Oslo	0.041	1.73	0.096	5.94
Sinus curve for daylight in Bergen	0.110	3.74	0.089	6.23
Sinus curve for daylight in Trondheim	0.200	4.57	0.315	18.61
Sinus curve for daylight in Stavanger	0.123	2.97	0.106	6.49
Dummy for Sundays and holidays	-0.121	-4.33	-0.429	-26.99
Dummy for Saturdays	0.044	1.68	-0.176	-12.01
Dummy for Easter week	-0.021	-0.29	-0.180	-6.29
Dummy for Ascension weekend	-0.119	-1.21	-0.051	-1.14
Dummy for Whitsunday weekend	0.215	2.75	0.066	1.41
Dummy for Christmas holiday	-0.274	-3.46	-0.161	-6.10
Linear time trend (years since end of 1989)	-0.030	-8.17	0.050	23.21
Overdispersion parameter	0.056	6.16	0.129	56.91
Log-likelihood	-14680.22		-32166.00	
Number of observations	11359		9924	

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[3] Since, in the sample, there are few – if any – cases in which a low rate of studded tyre use coincides with heavy snowfall or deep snow, the curves for rates 0 and 0.25 are not extended all the way through the range of variation for snowfall or snow depth.

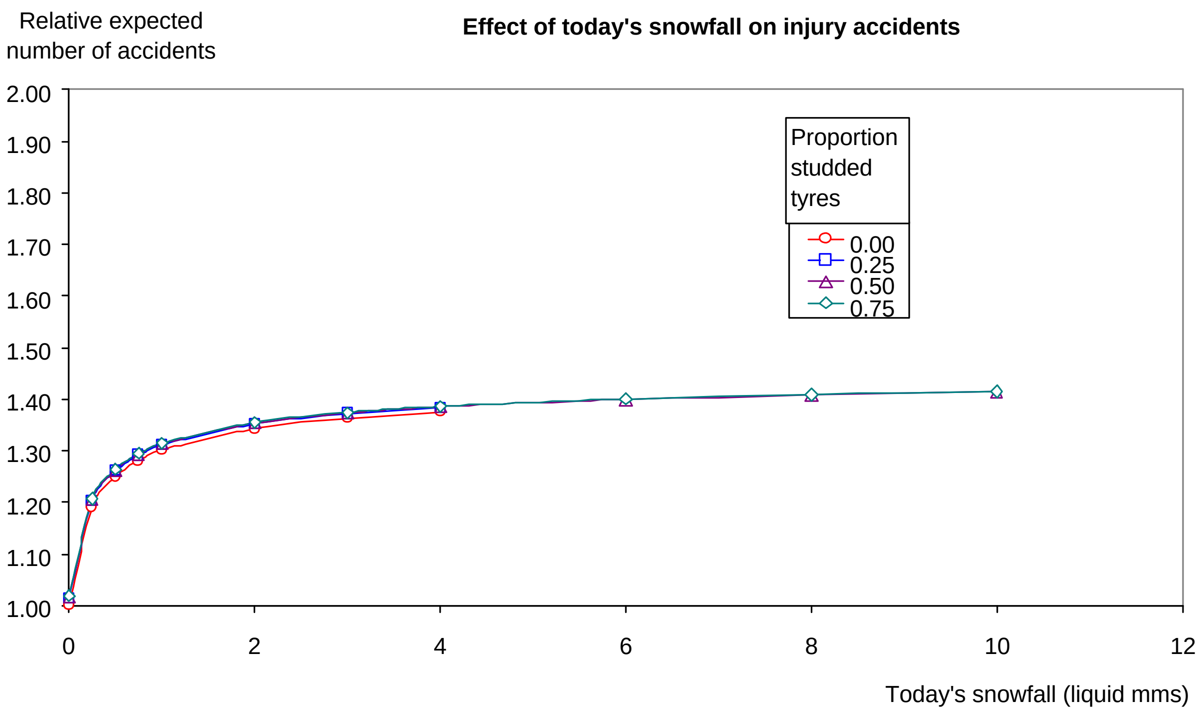

Figure 2: Estimated partial relationship between ***injury accident*** *frequency and* ***today's snowfall****. Numerical example for days with frost and 5 cms accumulated snow depth. Sample I.*

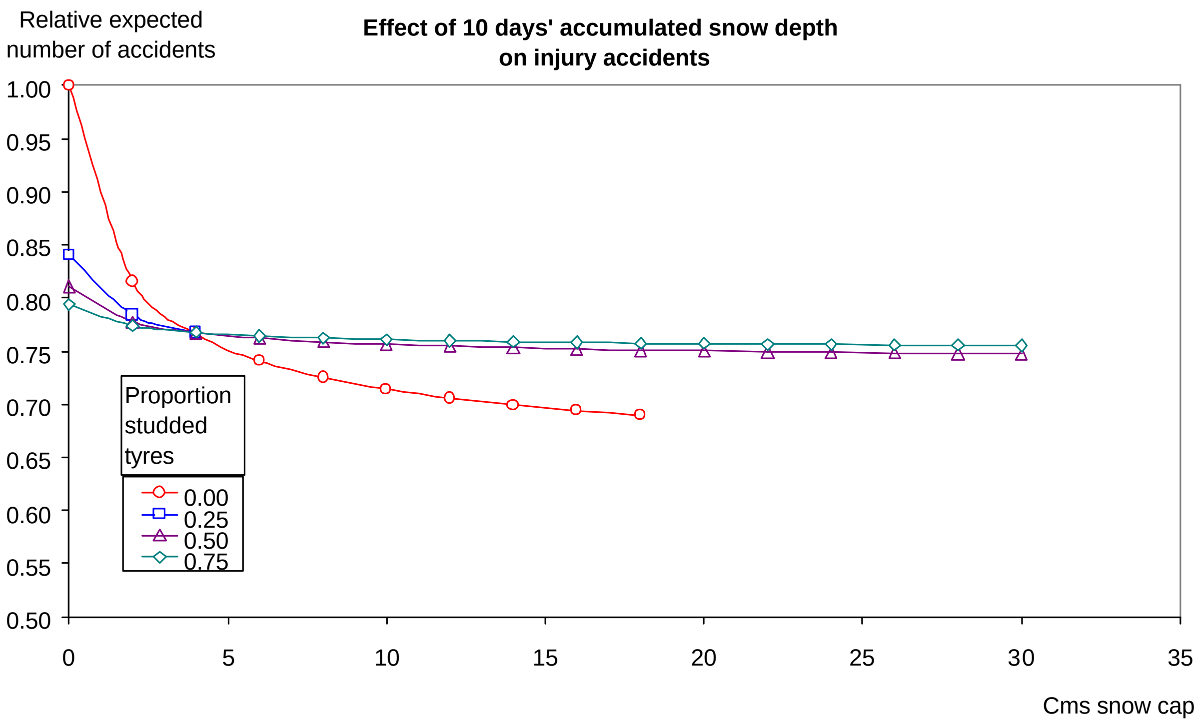

Figure 3: Estimated partial relationship between ***injury accident*** *frequency and 10 days'* ***accumulated snow depth****. Numerical example for days with frost but no snowfall. Sample I.*

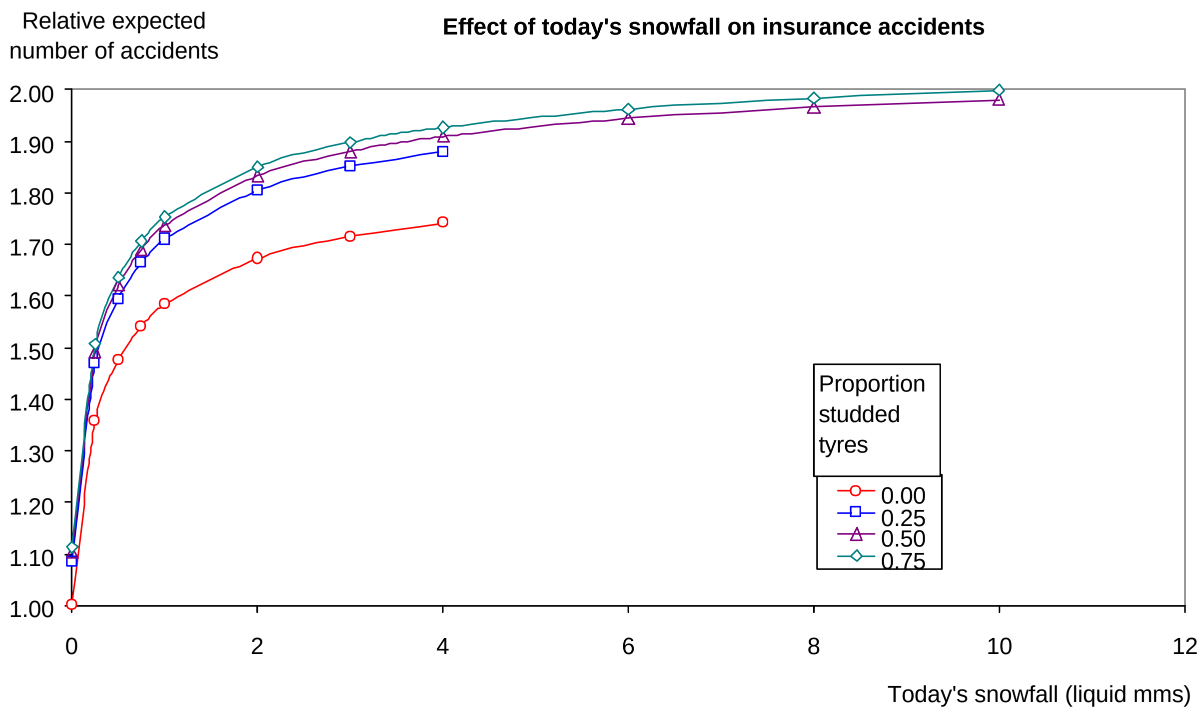

Figure 4: Estimated partial relationship between ***insurance accident*** *frequency and* ***today's snowfall****. Numerical example for days with frost and 5 cms accumulated snow depth. Sample II.*

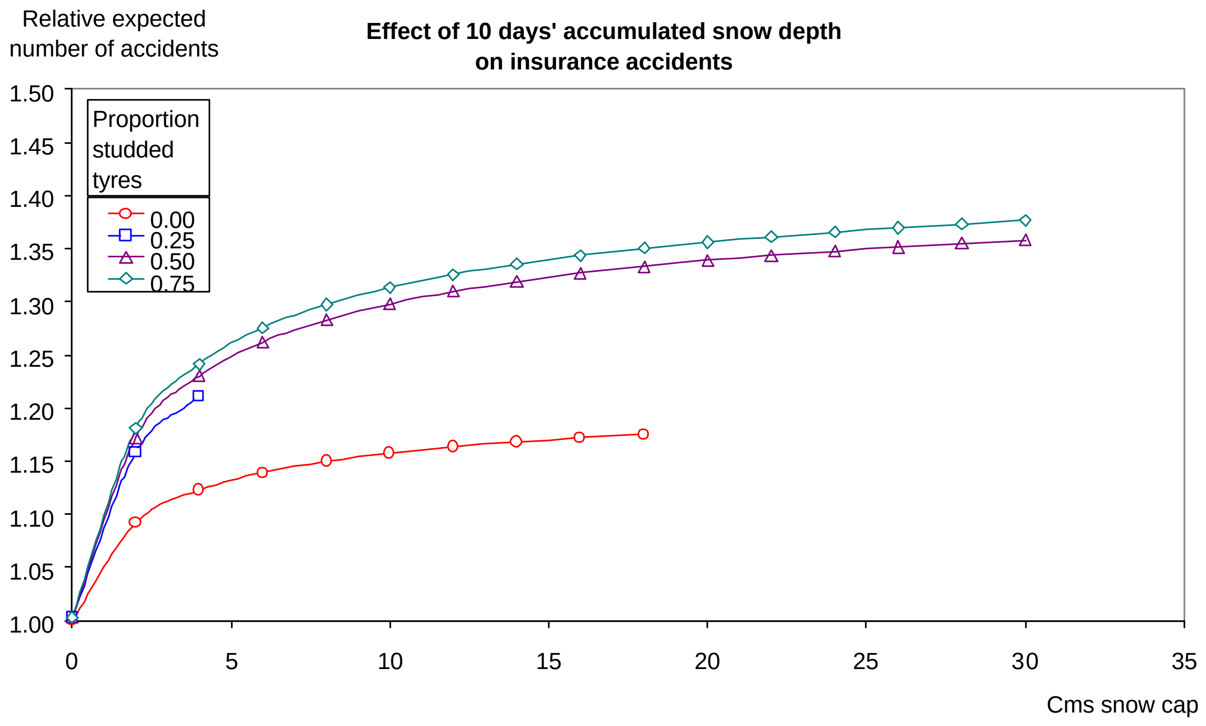

Figure 5: Estimated partial relationship between ***insurance accident*** *frequency and 10 days'* ***accumulated snow depth****. Numerical example for days with frost but no snowfall. Sample II.*

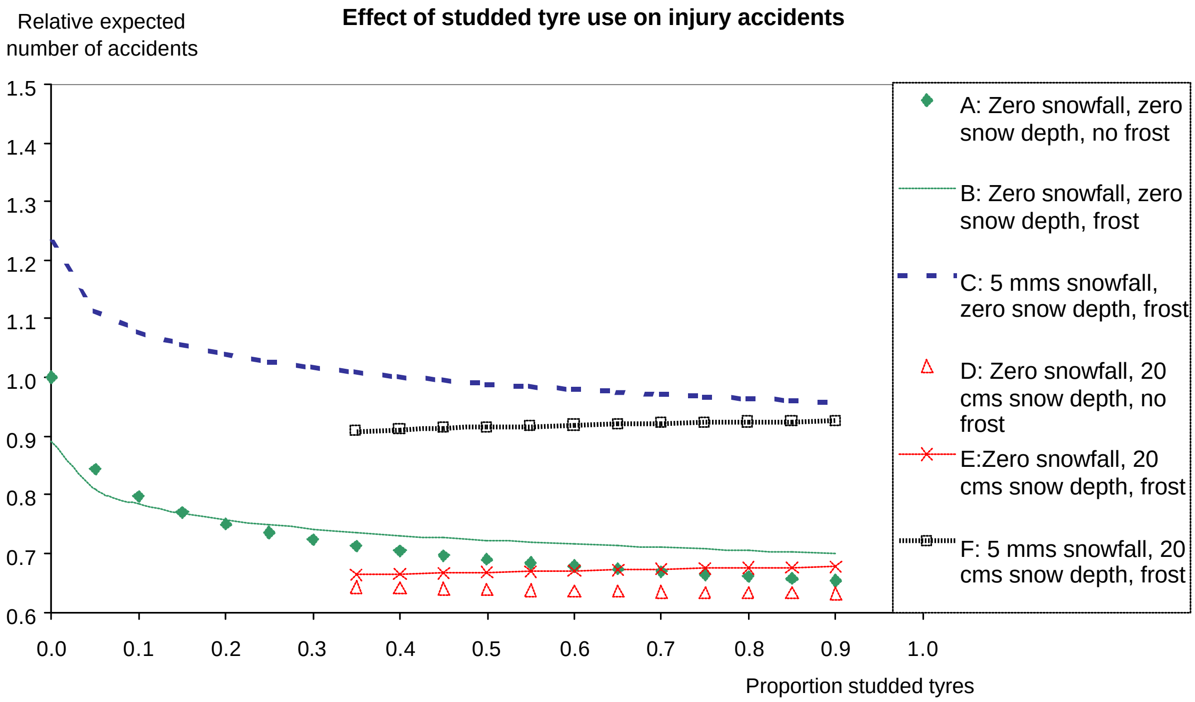

*Figure 6: Estimated partial relationship between **injury accident** frequency and **studded tyre use**, calculated under varying weather conditions. Sample I.*

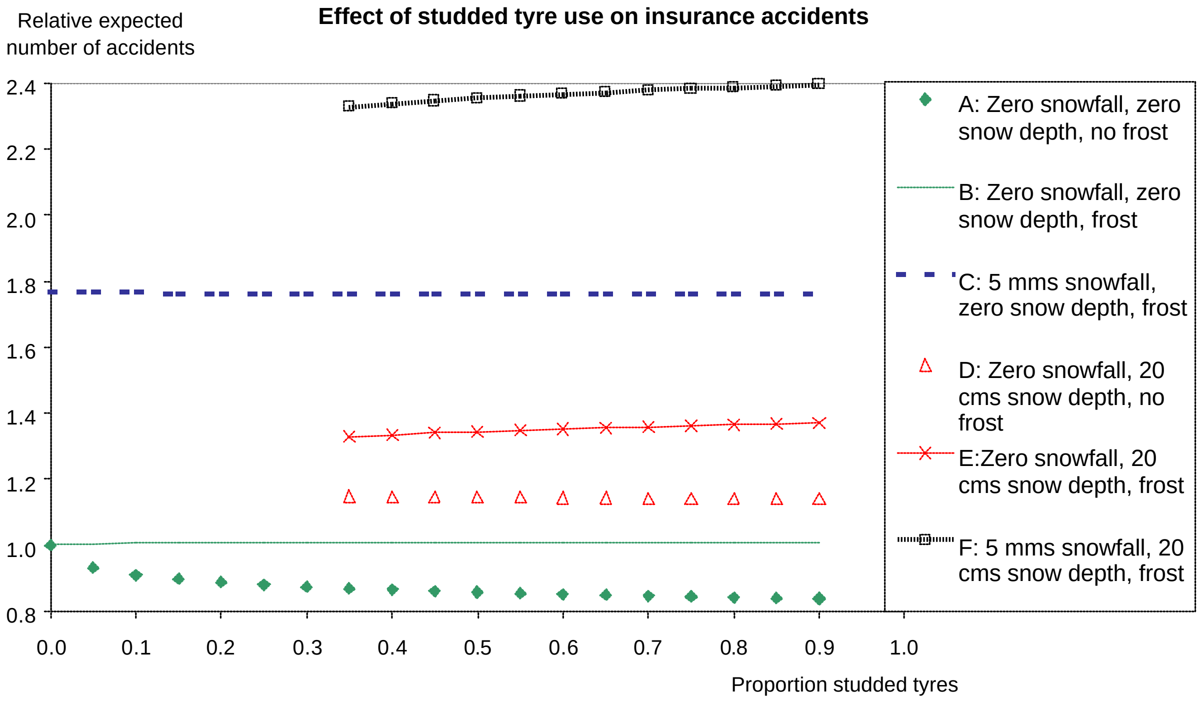

*Figure 7: Estimated partial relationship between **insurance accident** frequency and **studded tyre use**, calculated under varying weather conditions. Sample II.*

Table 2: Estimation results in least squares regression model for mean daily speed..

Independent variable	Coefficient	t-value
LNP: log(per cent studded tyres + 1)	0.077	4.483
X1: today's snowfall (mms as melted)	-1.124	-2.714
X2: 10 days' accumulated snow depth (cms) $^{0.5}$	-0.953	-6.283
X3: frost	0.530	3.260
X4: today's rainfall (mms) $^{0.5}$	-0.070	-4.949
X5: X1 × log(per cent studded tyres + 1)	0.169	1.717
X6: X2 × log(per cent studded tyres + 1)	0.184	5.046
X7: X3 × log(per cent studded tyres + 1)	-0.244	-5.777
X8: X4 × log(per cent studded tyres + 1)	0.014	2.619
Bergen traffic count	-0.759	-11.312
Trondheim traffic count	-0.746	-8.362
Stavanger traffic count	-0.996	-16.950
Bergen dummy	52.627	184.808
Trondheim dummy	61.017	185.051
Stavanger dummy	60.842	227.000
Sinus curve for daylight in Bergen	0.093	1.926
Sinus curve for daylight in Trondheim	-1.283	-18.204
Sinus curve for daylight in Stavanger	-0.576	-12.572
Dummy for Sundays and holidays	1.323	19.295
Dummy for Saturdays	0.882	14.874
Dummy for Easter week	0.458	4.414
Dummy for Ascension weekend	-0.136	-0.916
Dummy for Whitsunday weekend	0.011	0.071
Dummy for Christmas holiday	0.613	5.520
Linear time trend (years since end of 1989)	0.045	5.466
R^2	0.918	
Number of observations	5706	

One notes that the injury accident frequency does increase with snowfall, as expected. However, it decreases with the amount of snowfall during previous days. It seems natural to interpret this as a result of behavioural adaptation coupled with habit formation: once drivers have become used to wintry conditions, they know how to take account of them.

Figure 4 and 5 are blueprints of Figure 2 and 3, respectively, except that the former two show the effect on the sum of *PDO as well injury* accidents. Here, one notes that the risk of PDO accidents increases more sharply as a result of snowfall, and that even previous snowfall has an unfavourable effect on PDO accidents.

While in Figures 2 through 5 we have drawn contours in the two-dimensional space defined by the accident frequency and some weather variable, conditional on studded tyre use, in Figures 6 and 7 we reverse the roles. Here, curves are drawn conditional on certain weather variables, showing how studded tyre use affects accidents.

A rather perplexing picture evolves from these analyses. It seems that studded tyres have almost exactly the opposite effect of what is currently believed. They reduce accidents on days without snow, but result in more accidents on days exhibiting typical winter conditions (snow, frost).

In an attempt to understand the mechanisms behind these relationships, we also study the effect of weather and studded tyres on speed. Regression results are shown in Table 2.

The traffic volume enters the model in the form of an exponential function, given by $exp\left(f^{rt}/\bar{f}^{r}\right)$, where f^{rt} is the traffic flow recorded on day t in city r, and $\bar{f}^{r}$ is the sample average for city r. The coefficients of these terms are allowed to vary between cities, but come out quite similar.

Unlike the accident frequency equations, the speed equation includes a significant, direct term for studded tyre use (LNP in Table 2), in addition to the interaction terms with weather. Also, there appears to be significant interaction between studded tyre use and rainfall (X8).

In Figures 8 through 10 we show, in a format analogous to that of Figures 2 through 7, how speed varies with weather and studded tyre use.

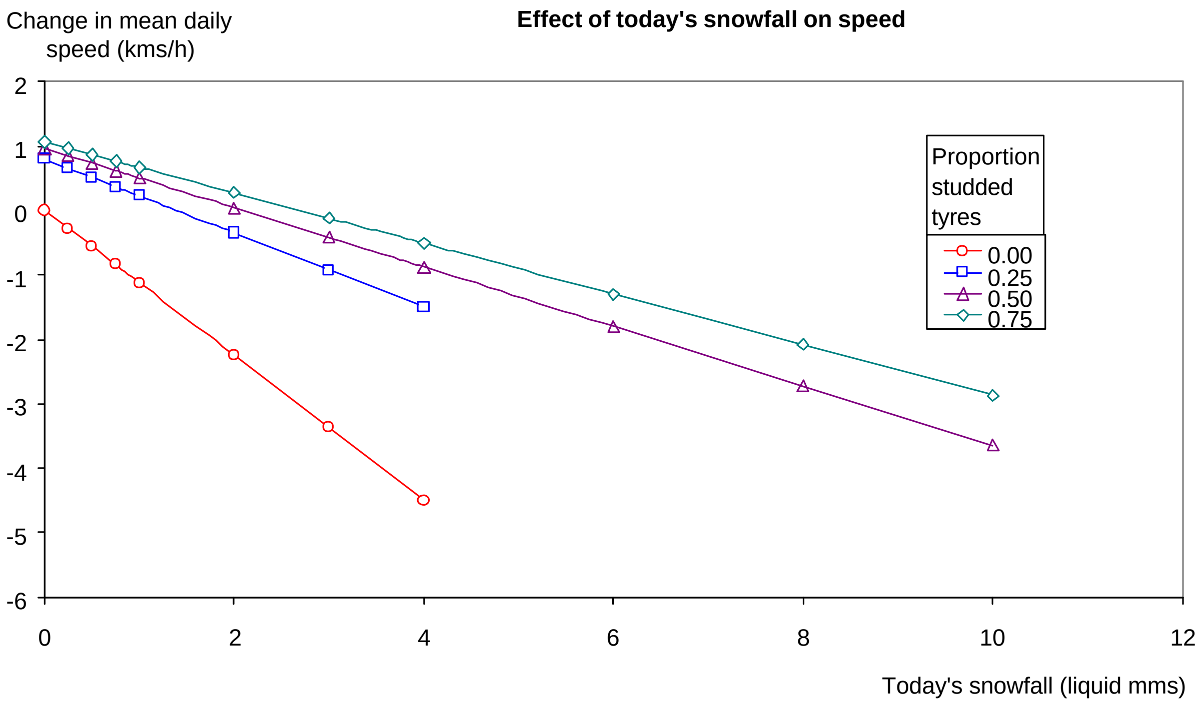

*Figure 8: Estimated partial relationship between **mean daily speed** and **today’s snowfall**. Numerical example for days with frost and 5 cms accumulated snow depth. Sample III.*

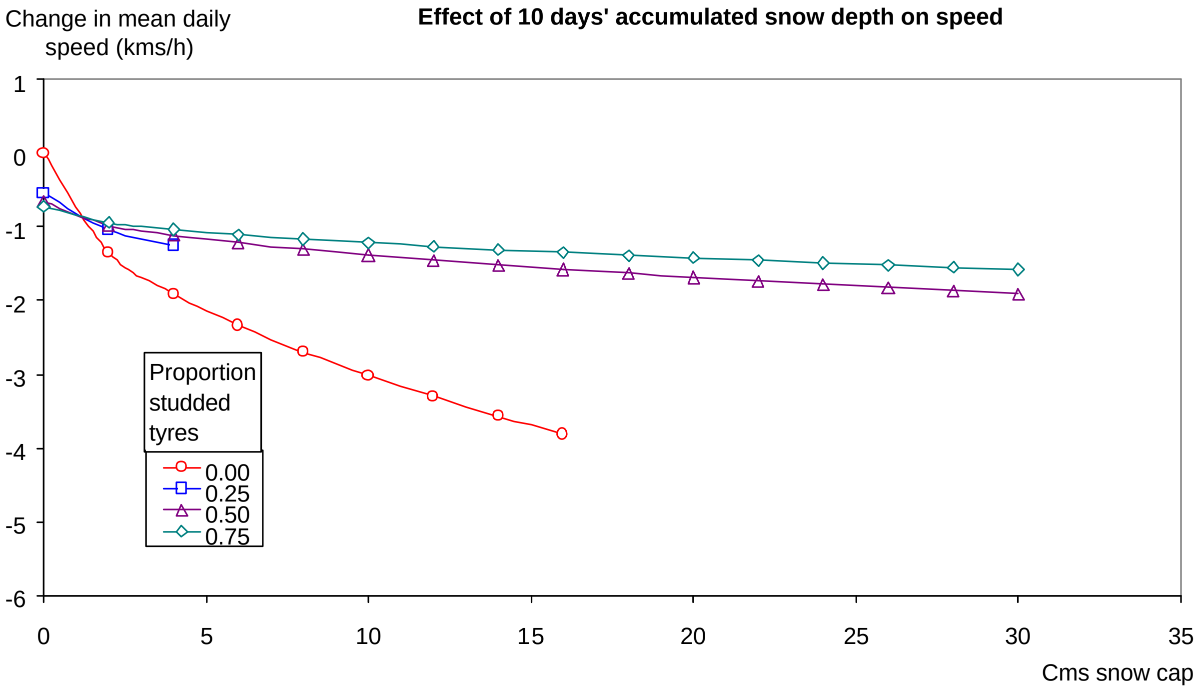

Figure 9: Estimated partial relationship between ***mean daily speed*** *and 10 days'* ***accumulated snow depth****. Numerical example for days with frost but no snowfall. Sample III.*

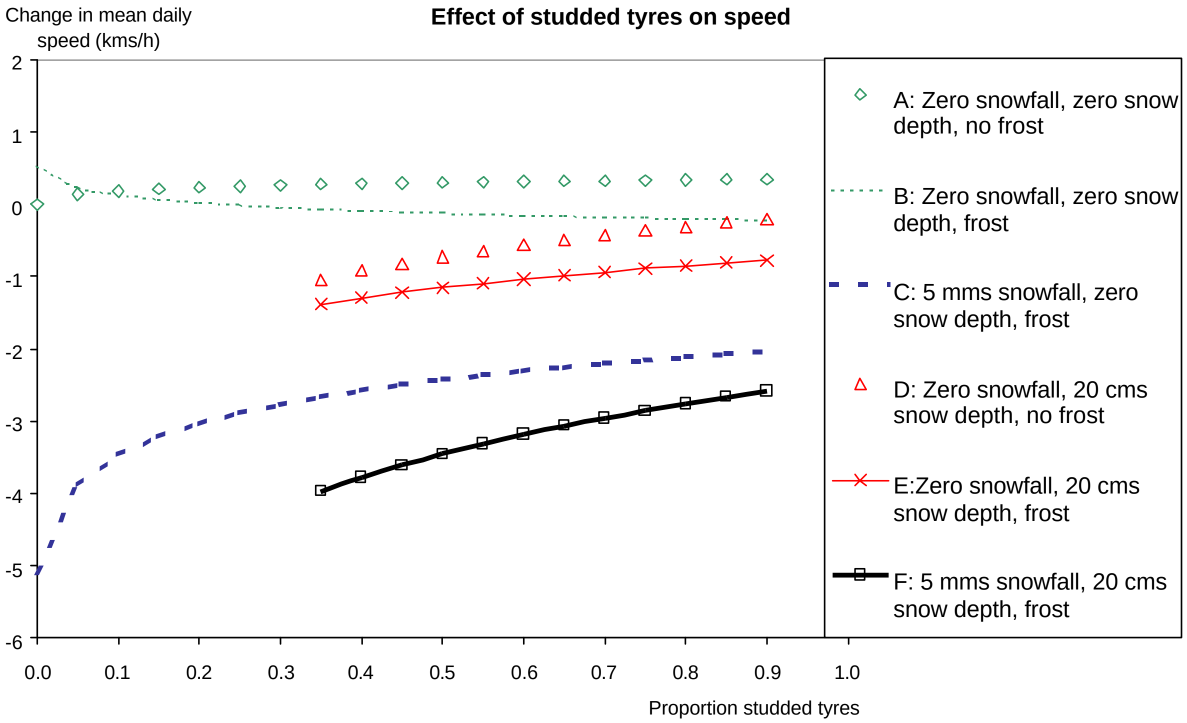

Figure 10: Estimated partial relationship between ***mean daily speed*** *and* ***studded tyre use****, calculated under varying weather conditions. Sample III.*

It turns out that speed varies in a way that to a large extent explains the effects of weather and studded tyres on the injury accident frequency.

From Figure 8, one notes that speed decreases markedly with instant snowfall, and more so the lower is the rate of studded tyre use. It also decreases sharply with the amount of snow on the ground, provided the use of studded tyres is low (Figure 9). Put otherwise, the use of studded tyres serves to increase the speed level, especially under heavy winter conditions (Figure 10).

We therefore seem to be faced with a clear case of *offsetting behaviour,* also known as *risk compensation* or *behavioural adaptation*.

This impression is strengthened when we compare the effects on injury accidents and insurance accidents, respectively. The latter accidents are, on the average, much less severe, as they are dominated by PDO crashes.

If drivers reduce their speed, the more severe accidents should go up relatively less, or down relatively more, that the less severe ones. This is precisely what we observe. While snowfall increases the frequency of insurance accidents by up to 100 per cent, the injury accident risk goes up by only 40 per cent. And while a snow cap on the ground tends to raise the number of insurance accidents, it actually reduces the injury accident risk.

Hence in both cases the average severity goes down, as would be expected if road users adapt their behaviour by lowering the speed.

It remains hard to understand why, as suggested by Figures 3 and 6, studded tyres would serve to reduce the risk when there is no snow on the ground, nor in the air. Here, it appears essential to realise that the weather measurements carry only limited information about the road surface conditions. It turns out, from inspecting the sample, that more than half the injury accidents happening on a snowy or icy surface, occur on days without snowfall. And some 28 per cent of these accidents take place when, as measured at the meteorological station, there is no snow on the ground.

The incidence of (accidents on) snowy or icy surfaces is, however, much lower on days without typical wintry weather. Encountering such road conditions are therefore, in a manner of speaking, more surprising to the road user than when he or she is «warned» by the presence of snow in the air and/or on the ground. The road user is less likely to have adapted his/her speed to the presence or absence of studs in the car’s tyres. In such situations the better friction offered by studded tyres may make a difference. We believe this *surprise effect* may help explain why studded tyres appear to reduce the accident rate snow-free winter days.

A third reason why our study may be expected to produce larger than usual effects on accidents is that *the aggregate feedback effect from studded tyre use to road surface conditions is included*. While ordinary tyres have the effect of packing any snow remaining on the pavement into a compact, icy substance, studded tyres serve to wear down this snow cap rather quickly. Thus, a high rate of studded tyre use has an effect on the road surface conditions experienced by all road users, regardless of tyre type. This effect is not captured in disaggregate studies of tyre choice and safety, such as the mailback survey made by Fosser and Sætermo (1995).

Overall effect

Our analyses show variable effects of studded tyre use, pointing in different directions, depending on the weather conditions. How do all of these effects add up, throughout a typical winter season?

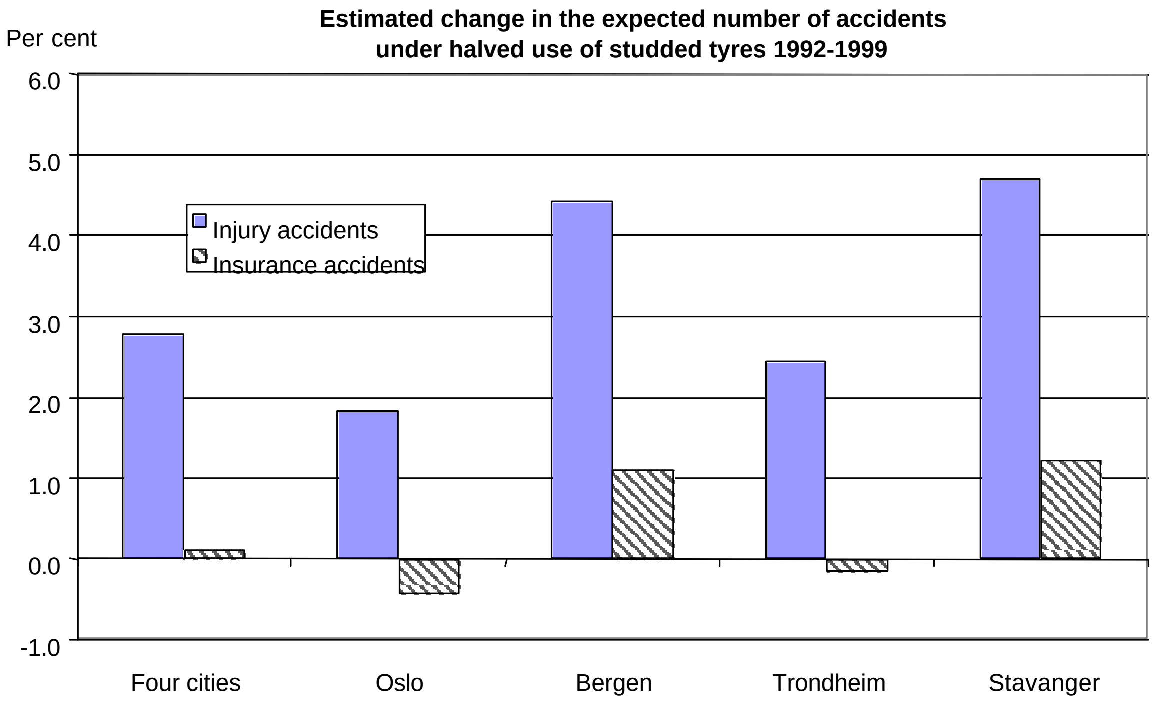

Figure 11: Calculated overall effects of a general 50 per cent reduction in studded tyre use. Sample enumeration estimates for four cities over the years 1992-1999. Sample II.

To answer this question, we performed a so-called *sample enumeration* exercise (see Ben-Akiva and Lerman 1985), in which, for each observation in Sample II, we recalculated the fitted values of the accident equations under the assumption that the rate of studded tyre use would everywhere be only half as high as in reality. Summing through the sample and comparing the result with the estimated expected actual number of accidents (i e, the original fitted values), we obtained the results shown in Figure 11.

By and large, a halved use of studded tyres is estimated to increase the number of injury accidents by 2 to 3 per cent, as reckoned over the entire winter season. Property-damage-only accidents appear to be more or less unaffected by the rate of studded tyre use.