International Transport Forum

A Framework for Assessing the Marginal External Accident Cost of Road Use and its Implications for Insurance Ratemaking

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Abstract

The external accident cost of road use is a function of the marginal relationship between road use and accidents, as expressed, for instance, by the elasticity. This elasticity is, however, not necessarily constant, but may be assumed to depend on the traffic volume as seen in relation to road capacity. Dense or congested traffic may force speed levels down, decreasing the risk of accidents or at least the average loss incurred given that an accident takes place. Relying on a large econometric accident model based on monthly cross-section/time-series data for all provinces of Norway, we derive non-linear empirical functions describing the relationship between road use and accidents and discuss their implications in terms of accident costs and externalities. The analysis reveals that there is probably a large accident externality generated by heavy vehicle road use, but that the marginal external accident cost of private car use is quite small, perhaps even negative. To the extent that it is positive, it is so in large part on account of public and private insurance. Contrary to what is frequently believed and maintained, auto insurance does not serve to internalise the cost of accidents. In fact, its primary purpose and effect is exactly the opposite. The adverse incentives created by insurance could, however, be mitigated by certain innovative approaches to ratemaking. Such schemes would ideally involve more decision variables than just the decision to drive. Incentives could, in principle, be attached to speeding, route choice, vehicle choice, safety equipment, or time of day/week/year.

1. The role of auto insurance

It is a frequently overlooked fact that the primary purpose of auto insurance is to externalise risk.

Without such externalisation, and assuming that drivers and car owners retain full liability for any damage caused to themselves or to other road users, a moment's inattention at the wheel would be sufficient to cause immediate financial ruin to any given car driver, except perhaps to the very wealthiest ones. In such a situation only the most affluent or careless citizens would risk producing their own motor transport services, i e to drive their own car.

It would mean the end of modern road transport as we have come to know it – as a complex and highly flexible system dominated by the private car alongside a variety of large and small professional operators. Only public operators large enough to be self-insured would be able to enter the market.

Auto insurance is thus a *sine qua non* for modern transport. One might, however, ask the question whether the share of (marginal) cost that is externalised through private and public insurance is optimal, or whether it would be possible to design schemes that are less prone to moral hazard and adverse incentives.

To provide a formal framework for this assessment, we shall start by looking at the concept of an externality.

2. Externalities

It is widely recognised that road transport is an activity characterised, at least occasionally, by large external costs. Such externalities may include *accidents*, *environmental effects*, *congestion*, and *road wear*.

An externality (external cost) is an adverse (side-)effect of production or consumption that is not considered by the decision-maker. More precisely, one might say that[1]

> an *external effect* exists when an agent's utility (or production) function contains a real (i e, non-monetary) variable, whose actual value depends on the behaviour of another agent, who does not take this effect of his behaviour into account in his decision making process.

Note that, according to this definition, *externalities operate at the disaggregate level*. That is, for an externality to be present, it is sufficient that there is a cross effect between two *individual* decision-makers. Even if both individuals happen to be, e g, motorists, so that the cross effect is – in a sense – internal to the *club* of road users, we are faced with an externality in the relevant economic sense.

The issue of *road accident* externalities has been the subject of several important studies[2]. A common theoretical finding resulting from these studies is that the external accident cost of

[1] Our formulation builds on Verhoef (1996), who in turn relies on Mishan (1971) and Baumol and Oates (1988).

road use is a function of the marginal relationship between road use and accidents, as expressed, for instance, by the elasticity.

However, very few studies provide well-founded empirical evidence as to the (range of) value(s) of this elasticity. In the words of Newbery (1988:171),

> "The key element in determining the accident externality cost is […] the relationship between traffic flow and accident rates, where the evidence is sketchy, to say the least."

The main idea of this paper is suggest an analytical framework for such an assessment, and to provide some sketchy, empirical information on the issue.

3. Assessing the marginal external accident costs of road use

Let us start out by noting that an externality, as defined above, is always related to some dimension of behavioural choice as faced by a decision maker.

Road users are continuously making decisions along a number of such dimensions. The most basic choice is whether or not to travel at all, and – more generally – how far to travel, and by what mode. We shall refer to the decision to travel a certain distance by road, using some kind of vehicle, or walking, as the *road use* decision.

Other behavioural decisions include speed, departure time, route choice, and the driver's level of attention/distraction. We will be returning briefly to these aspects in section 6 below.

When we want to discuss – with some precision – how transport policy, accident countermeasures, automobile insurance or other behavioural constraints may affect road use and accident costs, and indeed their interrelationship, we shall be helped by a rigorous mathematical framework. Such a framework should ideally reflect the fact that road users are a strongly heterogeneous group, in terms of size, speed, vulnerability, and external and internal risk. The pedestrian is, in most aspects, very different from the 40-ton truck.

Having established such a framework, we shall use it to derive some first results regarding the marginal accident cost of road use and its division between internal and external components. We shall, in principle, distinguish between all relevant road user categories. By way of illustration, we shall apply certain empirical results to characterize at least two important road user categories – those of light and heavy motor vehicles, respectively.

A certain part of the accident cost will almost always be internal. No insurance policy can remove the pain, suffering, physical impairment or personal grief suffered by a road user involved in an accident, or by this person's relatives and friends. However, in western societies a large part of the non-emotional cost is covered through social and private insurance. This applies to medical treatment, production loss, disability benefits, and material damage on vehicles and infrastructure.

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[2] See, e g, Lave (1987), Newbery (1988), Jones-Lee (1990), Vitaliano and Held (1991), Jansson (1994), Elvik (1994), Persson and Ödegaard (1995), Mayeres et al (1996), European Commission (1996), Maddison et al (1996), Jansson and Lindberg (1998), and Christensen et al (1998).

Let $\boldsymbol{v} = (v_1 v_2 v_3 \cdots)$ be the a vector of traffic volumes, as measured in vehicle kilometres driven within each vehicle class, let $c(\boldsymbol{v})$ denote the *private, unit accident cost of road use* at traffic volumes $\boldsymbol{v} = (v_1 v_2 v_3 \cdots)$, and let $b(\boldsymbol{v})$ denote the corresponding *cost borne by other people than the road user himself*. Denoting by $K(\boldsymbol{v})$ the *total* accident cost of road use, we can write

$$K(\boldsymbol{v}) \quad = \quad v_A \cdot k(\boldsymbol{v}) \quad = \quad v_A \cdot b(\boldsymbol{v}) + v_A \cdot c(\boldsymbol{v}), \tag{1}$$

where $k(\boldsymbol{v})$ is the *average accident cost* per overall vehicle kilometre and $v_A = \sum_j v_j$ is the overall amount of vehicle kilometres driven.

Also, let

$$q_j(\boldsymbol{v}) \quad = \quad \frac{c_j(\boldsymbol{v})}{k_j(\boldsymbol{v})} \quad = \quad \frac{c_j(\boldsymbol{v})}{b_j(\boldsymbol{v}) + c_j(\boldsymbol{v})} \tag{2}$$

denote the share of the accident cost which is borne by the type *j* individual road user himself. To simplify the argument, assume that $q_j(\boldsymbol{v}) = q_j$ is a constant not depending on the traffic volume.

Denote by $\alpha(\boldsymbol{v})$ the mean cost (expected loss) per accident, by $\omega(\boldsymbol{v})$ the total expected number of accidents, and by $r(\boldsymbol{v}) = \omega(\boldsymbol{v})/v_A$ the overall *risk* level, i e the expected number of accidents per vehicle kilometre driven. Then we can write

$$K(\boldsymbol{v}) = \alpha(\boldsymbol{v}) \cdot \omega(\boldsymbol{v}) \quad \Rightarrow \quad k(\boldsymbol{v}) = \alpha(\boldsymbol{v}) \cdot \frac{\omega(\boldsymbol{v})}{v_A} = \alpha(\boldsymbol{v}) \cdot r(\boldsymbol{v}), \tag{3}$$

$$\varepsilon_j^K = \quad \varepsilon_j^\alpha + \varepsilon_j^\omega \quad \equiv \quad \frac{\partial \alpha}{\partial v_j}\frac{v_j}{\alpha} + \frac{\partial \omega}{\partial v_j}\frac{v_j}{\omega} \tag{4}$$

and

$$\varepsilon_j^r \quad \equiv \quad \frac{\partial r}{\partial v_j}\frac{v_j}{r} \quad = \quad \frac{\partial(\omega/v_A)}{\partial v_j}\frac{v_j}{(\omega/v_A)} \quad = \varepsilon_j^\omega - \frac{v_j}{v_A} \tag{5}$$

where, ε_j^ω, ε_j^r, and ε_j^α, respectively, are the overall *accident frequency*, *risk*, and *mean accident cost* elasticities with respect to traffic category *j*.

Under these assumptions, the marginal external accident cost of vehicle class *j* is given by the total marginal cost minus the average private cost taken into account by the road user:

$$\begin{aligned} \frac{\partial K(\boldsymbol{v})}{\partial v_j} - c_j(\boldsymbol{v}) \quad &= \quad k(\boldsymbol{v}) \cdot \left[\varepsilon_j^\omega + \varepsilon_j^\alpha\right]\frac{v_A}{v_j} - c_j(\boldsymbol{v}) \quad = \quad k(\boldsymbol{v}) \cdot \left[\left[\varepsilon_j^\omega + \varepsilon_j^\alpha\right]\frac{v_A}{v_j} - q_j \frac{k_j(\boldsymbol{v})}{k(\boldsymbol{v})}\right] \\ &= \quad \alpha(\boldsymbol{v}) \cdot r(\boldsymbol{v}) \cdot \left[\left[\varepsilon_j^r + \varepsilon_j^\alpha\right]\frac{v_A}{v_j} + 1 - q_j \frac{k_j(\boldsymbol{v})}{k(\boldsymbol{v})}\right], \end{aligned} \tag{6}$$

reducing to

$$\frac{\partial K(\mathbf{v})}{\partial v_A} - c(\mathbf{v}) \quad = \quad k(\mathbf{v}) \cdot \left[\varepsilon_A^{\omega} + \varepsilon_A^{\alpha} - q_A\right] \quad = \quad \alpha(\mathbf{v}) \cdot r(\mathbf{v}) \cdot \left[\varepsilon_A^{r} + \varepsilon_A^{\alpha} + 1 - q_A\right] \tag{7}$$

in the homogeneous traffic case, or if we do not distinguish between vehicle classes (Fridstrøm 1999).

The sign and size of the accident externality depends crucially on the *risk elasticity* with respect to the traffic volume. For all types of traffic considered together, this elasticity is equal to the elasticity of *accidents* with respect to traffic, minus one. It is, in other words, positive if and only if the number of accidents increases more than proportionately with the number of vehicle kilometres.

Assume, for the sake of the argument, that the mean cost of an accident is independent of the traffic volumes, i e $\varepsilon_j^{\alpha} = 0 \ \forall j$. In this case, there is a positive external accident cost generated by the marginal representative road user only in so far as his own share (q_A) of the average accident cost is smaller than the accident elasticity ε_j^{ω} (equation 7).

For a particular traffic category *j*, the relevant parameters determining the marginal external accident cost are the *partial accident frequency and cost elasticities, weighted by the inverse traffic share*, and the *internal share of accident costs adjusted to reflect the higher or lower cost of accidents involving type j vehicles* compared to the overall mean cost per accident (formula 6).

Since, in an "unsaturated" traffic environment, the number of possible two-party conflict situations may be thought to increase in relation to the *square* of the number of vehicles on the road, one might imagine that the accident elasticity (ε_A^{ω}) would be larger than unity in the early phase of the motorisation:

$$\omega(\mathbf{v}) \propto v_A^2 \quad \Rightarrow \quad \varepsilon_A^{\omega} = 2 \quad \Rightarrow \quad \varepsilon_A^{r} = 1 . \tag{8}$$

For such a case, Newbery (1988) points out that there would be an externality involved which would be at least equal to the total cost of the accident. (If $q_A < 1$, the externality would be even larger than the total cost of the accident.)

But as roads become crowded, traffic density is bound to affect driving behaviour, notably speed, thus forcing down the number of crashes, or at least the severity of their outcome[3]. Where on this curve are we? What are the values of key parameters such as q_j , ε_j^{r} and ε_j^{α} ? These are empirical questions that can, in principle, be resolved by appropriate financial and econometric analyses.

[3] See Shefer and Rietveld (1997) for an extensive discussion of this based on first principles.

4. Some empirical evidence

An increase in exposure, as measured in terms of vehicle kilometres travelled (VKT, here denoted v_j), must be expected to lead to an increase in accident frequency, although not necessarily a proportional one. On the other hand, an increase in traffic density, as measured, e g, in terms of average daily traffic (ADT), may have an opposite sign effect, on accident frequency as well as on severity, since speed is forced down in dense traffic. Neither of these relationships is necessarily linear.

Since, depending on spatial and temporal delimitations, the traffic density tends to be strongly correlated with the traffic volume, it is econometrically challenging to distinguish the former effect from the latter.

An attempt was, however, made by Fridstrøm (1999, 2000a), based on data set consisting of pooled, regional times series data set – 19 Norwegian counties as measured over 264 months. An important limitation to this data set is that, being at a rather coarse level of aggregation, it does not contain observations representative of seriously congested situations. Another caveat relates to possible econometric misspecification, in that spatial and temporal effects were constrained to be equal.

With these qualifications in mind, we exhibit, in Table 1, selected results from the econometric analysis. For a more thorough explanation and interpretation, see Appendix A.

Table 1: **Measures of partial association between injury accidents and overall, light vehicle and heavy vehicle road use, as estimated for Norwegian counties 1973-94. Minimal, mean and maximal sample point values**. *Source:* Fridstrøm (1999, 2000a)

Traffic category	Elasticity			Inverse traffic share times elasticity		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Total vehicle kilometres	0.484	0.494	0.506	0.484	0.494	0.506
Light vehicle kilometres	0.248	0.291	0.361	0.335	0.345	0.357
Heavy vehicle kilometres	0.181	0.202	0.236	0.909	1.321	1.974

In the table, we show imputed *injury accident frequency* elasticities (ε_j^{ω}, $j=A, L, H$) with respect to overall, light and heavy vehicle traffic volumes, as well as the measures $\varepsilon_j^{\omega}\left(v_A/v_j\right)$ entering the accident externality formula (6). Minimal, mean and maximum values, as resulting from evaluating the elasticities at each sample point, are shown.

The imputed elasticities do not vary a lot across the sample. The sample point elasticities with respect to *light* vehicle road use cluster between 0.25 and 0.36, with a mean of 0.291. With respect to heavy vehicle traffic, the imputed elasticities range from 0.18 to 0.24, with a sample mean of 0.202.

The elasticity is, in other words, consistently lower with respect to heavy vehicle road use than for light vehicles. This is, however, primarily due to the heavy vehicles' much smaller traffic share. In our sample, the light vehicle traffic volume is, on the average, six times larger than the heavy vehicle road use.

When correcting for the unequal traffic shares, by multiplying the elasticities by the inverse traffic share of each vehicle class, we note that the marginal accident effect of heavy vehicle traffic is 3.8 times larger than for light vehicles. Heavy vehicles are thus, in a sense, about four times more dangerous than light ones, in the sense of "producing" four times more injury accidents per marginal vehicle kilometre.

Owing to the pronounced variation in traffic mix across space and time, the marginal accident effect of heavy vehicles is more than twice as strong (1.974/0.909) at its sample maximum compared to its minimum value. For light vehicles, the corresponding effect varies by less than 10 per cent (0.357/0.335).

What about two-wheelers and pedestrians? Here, the empirical assessment of elasticities is more demanding, since reliable exposure data are not that readily at hand. It is particularly difficult to obtain comprehensive data sets that describe variations in pedestrian and bicyclist road use. An attempt was, however, made to construct proxy measures based on weather conditions, public transport supply and motorcycle fleet data.

In Figure 1 we summarize certain results relying on this approach. Note that to derive elasticities under constant road network supply, we must add together the "motor vehicle kilometres" and the "traffic density" variables, since these will change proportionately (see Appendix A).

Light and heavy vehicle exposure are seen to affect injury accident frequency as of 1994 in roughly[4] the way set out in Table 1, i e by an *own* elasticity of approximately one half (= 0.911 – 0.414). MC victims increase in response to light and heavy vehicle traffic by a *cross* elasticity of 0.763 (= 0.749 + 0.014), bicyclist injuries by 0.475 (= 1.079 – 0.604), and pedestrian injuries by a mere 0.137 (= 1.109 – 0.972).

The *own* elasticity of exposure for MC is estimated at 0.208. Motorcyclist injuries are, in a sense, more sensitive to increases in automobile traffic than to their own level of exposure. On might also note that the cross effect of MC exposure on car occupant or pedestrian injuries is practically negligible. With respect to injury accidents in general, the elasticity comes out at 0.026.

Considering, however, that (as of 1994) MCs represent only about 2 per cent of the total vehicle kilometres, we must multiply this elasticity by almost 50 to obtain an estimate of the marginal accident cost multiplier, comparable to the figures shown under "Inverse traffic share times elasticity" in Table 1. Hence MCs are seen to be just about as "dangerous" on the margin as heavy vehicles, with the big difference, however, that while a major part of the accident cost will normally be external to the heavy vehicle involved, motorcyclists are much more vulnerable and probably carry the main part of the risk themselves (confer section 5 below).

A fairly high "cross" elasticity of MC exposure may seem to apply to bicyclist injuries (0.254), but this is obviously an artefact – a reflection of the fact that the MC proxy, being based on weather conditions, also captures variations in bicycling.

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[4] The figures are not exactly the same, since in Table 1 we exhibit sample means, while in Figure 1 elasticities are evaluated as of the last year of observation (1994).

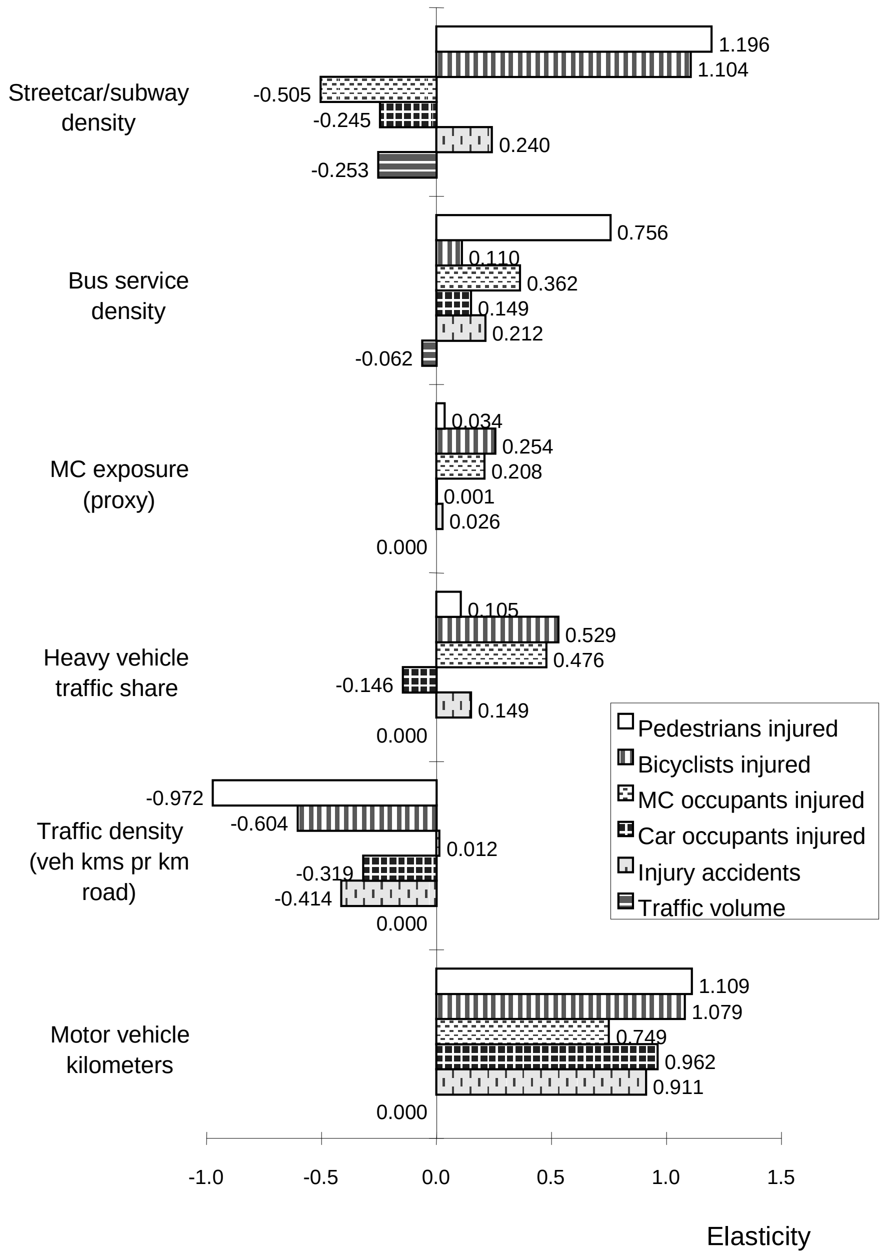

Figure 1: Estimated injury accident elasticities with respect to exposure, by road user category. Norway 1994. Source: Fridstrøm (1999, 2000a)

Interestingly, pedestrian injuries increase sharply with public transport supply, as witnessed by the elasticities of 0.756 and 1.196 found with respect to bus and tramway/subway ("light rail") supply, respectively. Walking being the main access/egress mode of public transport users, these exposure variables obviously also capture variations in pedestrian road use. Even bicyclist injuries are seen to increase with public transport supply, especially rail. This is so although enhanced public transport supply tends to constrain automobile exposure (elasticities of –0.062 and –0.253 for bus and light rail, respectively).

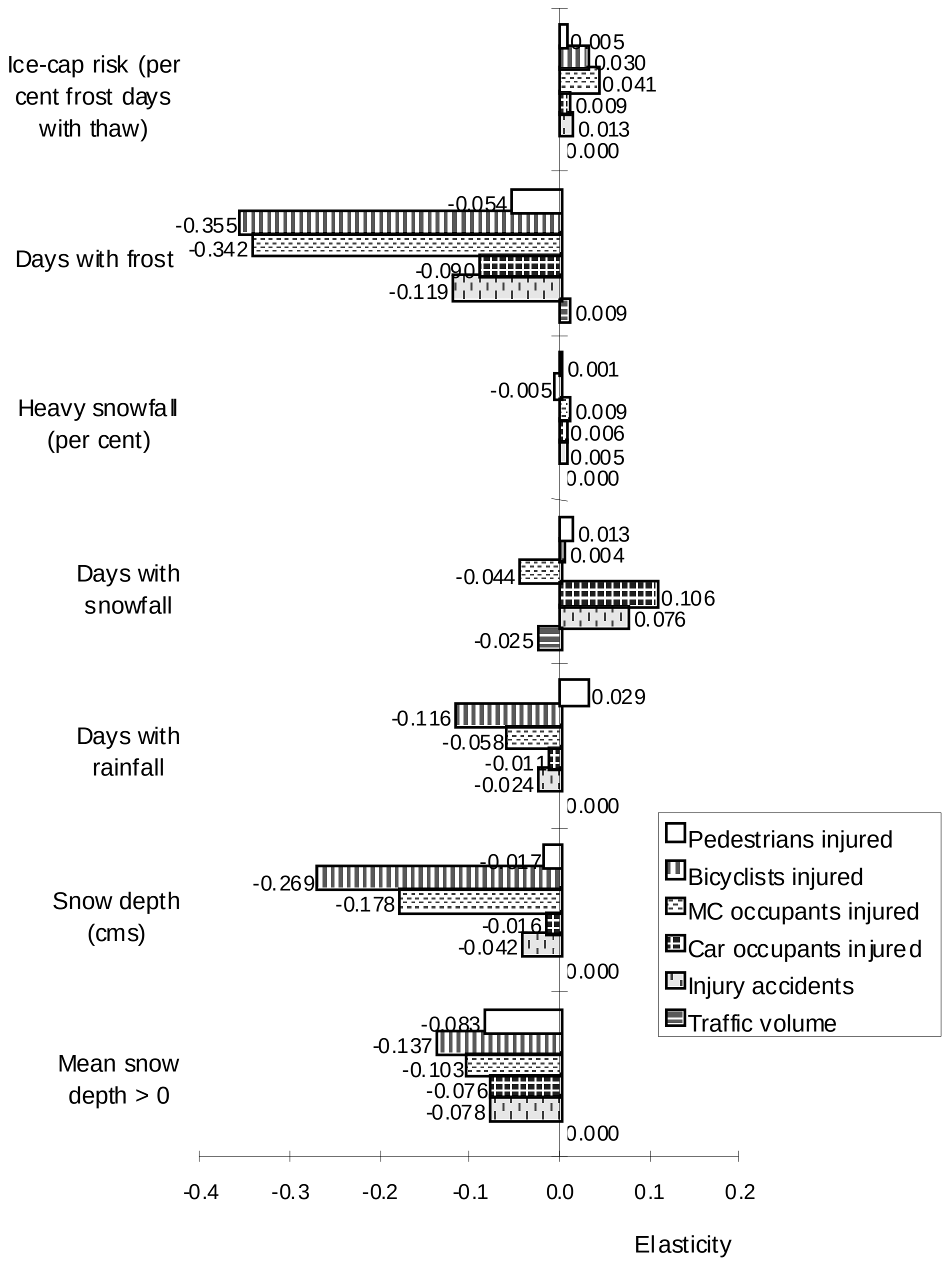

Figure 2: Weather effects. Injury accidents and victims by road user category. Norway 1994. Source: Fridstrøm (1999, 2000a)

In Figure 2, we exhibit certain estimation results concerning the impact of weather conditions, as applicable to Norway. It may seem surprising that typical winter conditions, such as frost and snow, do not have a more strongly unfavourable effect on risk. The main explanation is probably (i) behavioural adaptation, (ii) that in winter Norwegian motorists generally make use of snow tyres (with or without studs), and (iii) that they are rather well used to wintery driving conditions. It is worth noting, however, that the number of days with snowfall does have a risk increasing effect on the monthly injury accident toll, the accident frequency being 20-40 per cent higher during a month with snowfall every day compared to a snow-free month. The fact that two-wheeler exposure goes down during snowfall serves, however, to dampen the overall effect. Rainfall does not seem to affect the accident frequency in any significant way, except among two-wheelers, whose exposure obviously goes down. Later studies (Fridstrøm 2000b) suggest, however, that the injury accident frequency may increase by up to 10 per cent on rainy days.

Figure 3 exhibits analogous results concerning daylight, with the important distinction that here the indirect effect through motor vehicle exposure is not included. Four (inverse) measures of daylight are used. The expected number of injury accidents is 12 per cent higher in a month/county without evening daylight (i e, after 5 p m) and a further 11 per cent higher when the sun does not even rise above the horizon during the rush hours (7-9 a m and 3-5 p m) – a quite frequent phenomenon in northern Norway. Pedestrians are particularly hard hit by dark roads.

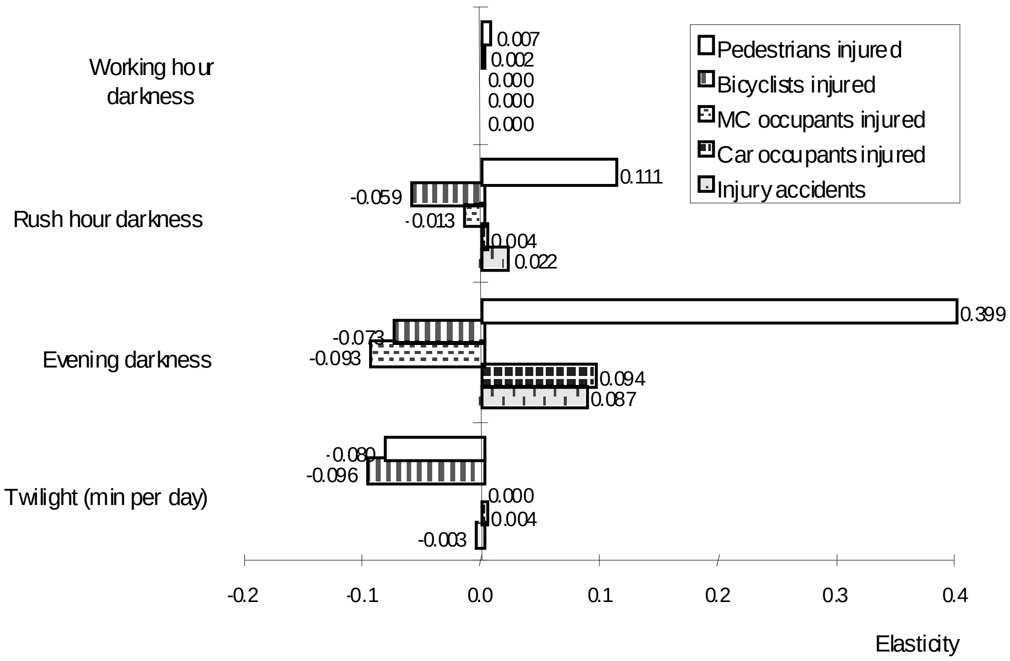

Figure 3: Direct daylight effects, conditional on motor vehicle road use. Injury accidents and victims by road user category. Norway 1994. Source: Fridstrøm (1999, 2000a)

5. Road accident externality assessments for light and heavy vehicles

According to the above estimates (Table 1 in view of equation 7), there is a positive external injury accident *cost* generated by the marginal representative road user only in so far as

$$q_A - \varepsilon_A^{\alpha} \quad < \quad \varepsilon_A^{\omega} \quad = \quad 0.494, \tag{9}$$

i e, roughly speaking, if the share of the accident cost borne by the individual road user himself *minus* the elasticity of the mean loss per accident is less than one half. In the opposite case, there is an external *benefit* involved.

To the extent that speed is forced down in denser traffic, it seems reasonable to assume that the mean loss per accident is a negative function of density, i e $\varepsilon_A^{\alpha} < 0$. Taking account of this would pull our externality estimate even further in the direction of a marginal *benefit*.

This applies in the case of homogenous traffic, or when we compute the average over all vehicle types. In the more detailed analysis, we find that for light vehicle users, the analogous mean "threshold" point is 0.345, and for heavy vehicles 1.321 (Table 1 in view of equation 6):

$$q_L - \varepsilon_L^{\alpha} \quad < \quad \varepsilon_L^{\omega} \quad = \quad 0.345 \tag{10}$$

$$q_H - \varepsilon_H^{\alpha} \quad < \quad \varepsilon_H^{\omega} \quad = \quad 1.321 \tag{11}$$

There is reason to believe that the share of the accident cost borne by the *heavy* vehicle operator is relatively small, and hence that there is a *positive* external accident cost linked to the marginal heavy vehicle kilometre. Assuming that, statistically speaking, the heavy vehicle operator sustains a private loss per kilometre amounting to no more than 32 per cent of the average unit cost of accidents, and that the mean loss per accident is unaffected by the traffic volume ($\varepsilon_H^{\alpha} = 0$), his road use typically gives rise to a positive marginal external accident cost which is *at least as large as the mean total cost of an accident*.

For light vehicle users, the sign of the externality is more questionable. Depending on the values attached to personal pain and suffering or to the loss of life or limb, and on the distribution of casualties between single vehicle accidents, unprotected road users, and multiple vehicle crashes, one might arrive at different conclusions. It is not obvious that $q_L \, k_L(\boldsymbol{v})/k(\boldsymbol{v})$ is smaller than one third (= appr 0.345), but if it is, this would probably be due, *inter alia*, to the fact that *significant parts of the accidents costs are usually covered by private and social insurance*. There is therefore, in our view, a potential positive external accident cost involved even for private car users, not *in spite of* automobile insurance, but *on account of* it.

Since, however, the measure $q_L \, k_L(\boldsymbol{v})/k(\boldsymbol{v})$ cannot possibly drop below zero, the external part of the marginal light vehicle accident cost is unlikely to be very large. If the elasticity of the mean accident cost with respect to road use is negative ($\varepsilon_L^{\alpha} \leq 0$), i e if severity decreases in denser traffic, it cannot, based on our estimates, exceed one third of the total accident cost on the average.

For a definite conclusion in this matter, research is needed to estimate the quantities $\alpha(\boldsymbol{v}), \varepsilon_j^{\alpha}$, q_j and $k_j(\boldsymbol{v})$ and their possible dependence on the traffic volume.

6. Decision variables relevant to insurance ratemaking

So far our analysis has been focused solely on one particular choice variable, viz. (i) the number of vehicle kilometres travelled (VKT) by car.

Other decision variables at the hand of the individual motorist are the (ii) speed, (iii) departure time, (iv) route choice, (v) level of attention/distraction. All of these will have a bearing on the risk which the motorist inflicts upon himself as well as on other road users. In addition, through the (vi) choice of vehicle, the driver or owner makes a trade-off between built-in safety and other vehicle characteristics, including price. Finally, insurance companies already practice widespread price discrimination according to (vii) the owner’s personal characteristics, such as age, gender, residential location, and accident record.

As for (i), it has been suggested (see, e g, Litman 2005) that motorists could pay for insurance ‘as you drive’, i e in exact proportion to the VKT. This would mean that the motorist faces a small marginal cost of going the extra mile, instead of the stepwise fixed cost characterising most insurance policies today. While implying a small step in the right direction, this scheme is unlikely to provide a large enough impetus to reverse the sign of the insurance incentive from adverse to favourable.

The idea of linking insurance premiums explicitly to certain observable aspects of risk-taking behaviour, such as (ii) (excessive) speed, may seem more promising. Recent technological advances may, in principle, allow for rather sophisticated systems by which motorists are charged according to their speed, or in response to speeding (i e, breaking the speed limit).

Another, similar idea is to make the premium responsive to traffic offenses of any kind, as recorded, e g, through the demerit point system, wherever such a system is in place.

The third possible choice variable, (iii) departure time, would influence risk *inter alia* through its correlation with daylight, season, etc. It has been suggested that novice drivers should have restricted rights, so as to avoid their driving at the most hazardous times of the day or week (e g Saturday night). Rather than regulating this by law, one could imagine introducing an economic incentive, differentiating the premium in ‘pay-as-you-drive’ insurance by time of day.

Similarly, it could be possible to charge according to (iv) the risk level of the road chosen. This might channel a larger share of traffic onto the safest kinds of road, giving rise to certain aggregate safety benefits.

Charges based on the fifth behavioural aspect, (v) the level of attention, or the use of cell phones or other distractions, are harder to implement, for the simple reason that these aspects are not systematically observable.

One major obstacle to the implementation and enforcement of such schemes is that the vehicle owner may not be identical to the driver. This fact also reduces the effectiveness of the insurance companies' attempt to differentiate the premium according to (vii) the *owner's* personal characteristics (age, gender, zone of residence, accident record, driver's license seniority, medical record, etc).

Another hurdle relates to our concerns about privacy – an issue, however, that had apparently found an acceptable solution in the proposed Dutch road pricing scheme[5].

One opportunity that is already being exploited is differentiation according to (vi) vehicle characteristics. It is conceivable that this scheme could be taken a step further, by explicitly honouring certain technological safety devices, such as electronic stability control and other advanced driver assistant systems (ADAS). Such an approach would, however, presuppose fairly reliable knowledge of the marginal risk reduction associated with each particular safety device, an assessment that would have to take proper account of behavioural adaptation and similar rebound effects.

7. Summary and conclusion

Judging by the analysis presented herein, it is *not* true, as is often maintained, that the accident risk is largely independent of the traffic volume. Nor is it true that the *risk elasticity* with respect to road use is positive. This elasticity appears to be close to zero when congestion is assumed constant, but distinctly smaller than zero when congestion (traffic density) effects are taken into account.

The analysis reveals that there is probably a large accident externality generated by heavy vehicle road use, but that the marginal external accident cost of private car use is quite small, perhaps even negative. To the extent that it is positive, it is so, not in spite of auto insurance, but – at least partly – *on account of* it.

Motorcycle use appears to be just as dangerous on the margin as heavy vehicle use, involving, however, most probably a significantly smaller *external* accident cost share.

It should be remembered that the primary purpose and effect of auto insurance is to externalise risk. The adverse incentives created by insurance could, however, be mitigated by certain innovative approaches to ratemaking. Such schemes would ideally involve more decision variables than just the distance driven. Incentives could, in principle, be attached to speeding, route choice, vehicle choice, safety equipment, or time of day/week/year. Bonus-malus systems, which are already widely practiced, could perhaps become even more sophisticated, so as to assign a larger share of the accident cost to the motorist or vehicle owner involved.

In the best of cases, these measures, if all implemented, could help reduce the adverse incentive implicit in automobile insurance. As of today, the economic incentive towards safe driv-

[5] This scheme implied that every vehicle be equipped with a smart transponder, i e a unit that not only recorded all the movements, but also calculated and summed up the appropriate charges. While the vehicle owner would be able to check all entries by connecting the transponder to his computer, only the weekly or monthly aggregate charge would be relayed to the collection office.

ing may seem surprisingly small. There is potentially considerable room for improvement by bringing market incentives more explicitly into the driver's or vehicle owner's decision process.

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Appendix A: Econometric analyses

A.1. A Box-Tukey regression model based on pooled regional time series

In brief, the following Box-Tukey[6] regression model was estimated on monthly data for Norwegian counties:

$$ln(y_{tr}+a)=\beta_1\, ln(v_{trA})+\beta_2\, ln\left(\frac{v_{trH}}{v_{trA}}\right)+\beta_3\left(\frac{v_{trA}}{l_{tr}}\right)^{(\lambda_3)}+\sum_{i>3}\beta_i x_{tri}^{(\lambda_i)}+u_{tr}\,. \qquad (12)$$

Here, y_{tr} denotes the number of *accidents or casualties* of some kind during month *t* in region *r*, *a* (= 0.1) is a Box-Tukey constant, v_{trA} is the *total (overall) traffic* volume (vehicle kilometres driven), v_{trH} is the corresponding *heavy vehicle traffic* volume, l_{tr} is the *length of the (public) road network*, x_{tri} (*i>3*) denote all the other independent variables of the model (of which there are about 45)[7], u_{tr} is a normally distributed random disturbance term, β_i are regression (slope) coefficients, and λ_i are Box-Cox (curvature) parameters[8].

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[6] See Tukey (1957), Box & Cox (1964).

[7] In broad terms, these variables include public transportation supply, road infrastructure and maintenance expenditure, population, vehicle stock, daylight, weather, calendar effects, geographic characteristics, legislation, access to alcohol, and reporting routines.

[8] The Box-Cox parameters of the dependent and the first two independent variables have been fixed at zero, translating these into logarithmic transformations.

β_1 is the general exposure (*traffic volume*) coefficient, β_2 is the coefficient for the *share of heavy vehicles*, while β_3 measures the separate effect of *traffic density*, as given by the number of vehicle kilometres divided by the number of road kilometres[9,10].

A.2. Elasticity formulas

In this model the elasticity of $\omega_{tr} \equiv E[y_{tr}]$ with respect to a variable x_{tri}, as defined at each sample point, is given by[11]

$$El[\omega_{tr}; x_{tri}] \equiv \frac{\partial \omega_{tr}}{\partial x_{tri}} \cdot \frac{x_{tri}}{\omega_{tr}} = \beta_i \cdot x_{tri}^{\lambda_{xi}} . \tag{13}$$

The elasticity is, in other words, generally not constant, but depends on the level of the independent variable and on the value of its Box-Cox parameter.

With a little algebra, one can derive elasticity formulas for the road use variables of interest. Assume, for the sake of argument, that the heavy vehicle share of the traffic volume (v_{trH}/v_{trA}) or the length of the road network (l_{tr}) does not change. In such a case, we can write the elasticity of the dependent variable with respect to the traffic volume (v_{trA}) as

$$\varepsilon_{trA}^{\omega} = \beta_1 + \beta_3 \left(\frac{v_{trA}}{l_{tr}} \right)^{\lambda_3} . \tag{14}$$

This elasticity depends, in other words, on the traffic density, and on no other variables. It is a decreasing function of the traffic density if and only if

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[9] We use the term "*traffic density*" in a sense different from the normal usage in traffic flow analysis. In this paper, "traffic density" means "vehicle kilometres per kilometre road per month". Our "density" measure is thus interpretable as 30 times the "average daily traffic (ADT) characterising the county", i e as the monthly traffic flow as averaged over "all points" on the county's network. The terms "*traffic volume*" and "*road use*", on the other hand, are used synonymously with "the number of vehicle kilometres (per county and month)". Thus the traffic volume is equal to the traffic density times the length of the road network.

[10] The accident regression model is part of a larger econometric system of equations, called TRULS, in which even car ownership, road use, seat belt use, road casualties, and accident severity are explained. For a more comprehensive account of this model, and on how we obtain accurate vehicle kilometre measures v_{trj} for each province and month, we refer the reader to Fridstrøm (1999a or 1999b).

The model is estimated by means of the BC-GAUHESEQ algorithm of the TRIO computer package (Liem et al 1993, Gaudry et al 1993), which provides simultaneous maximum likelihood estimates of all parameters, including parameters defining the disturbance (co)variance structure. To be precise, we include 1st and 14th order temporal autocorrelation terms and a disturbance variance specification consistent with the assumption that the accident counts y_{tr} are Poisson distributed. The small Box-Tukey constant (*a* = 0.1) makes sure that $ln(y_{tr} + a)$ has finite variance

[11] In deriving these elasticities we disregard the small Box-Tukey constant. To correct for this inaccuracy, one should multiply all elasticities by $(\omega + a)/\omega$, ω being the expected number of accidents or casualties.

$$\frac{\partial \varepsilon_{trA}^{\omega}}{\partial (v_{trA}/l_{tr})} = \beta_3 \lambda_3 \left(\frac{v_{trA}}{l_{tr}} \right)^{\lambda_3 - 1} < 0 , \tag{15}$$

i e if and only if β_3 and λ_3 have opposite signs.

The Box-Cox regression model is such as to let the empirical evidence (the data) determine, not only the *sign* and *slope* of the partial relationships between dependent and independent variables, but also on the *shape* (curvature) of these relationships. Implicitly, this process also amounts to *estimating* (rather than assuming) how the elasticities depend on certain key variables, such as – in this case – the traffic density.

Next, let us relax the assumption that the mix between light and heavy vehicles is constant, and compute elasticity formulas with respect to either type of vehicles. Noting that

$$v_{trA} \equiv v_{trL} + v_{trH} , \tag{16}$$

where v_{trL} is the number of *light vehicle kilometres* driven[12], we have, after some algebra,

$$\frac{\partial \omega_{tr}}{\partial v_{trL}} \frac{v_{trL}}{\omega_{tr}} \equiv \varepsilon_{trL}^{\omega} = \left[\beta_1 - \beta_2 + \beta_3 \left(\frac{v_{trA}}{l_{tr}} \right)^{\lambda_3} \right] \cdot \frac{v_{trL}}{v_{trA}} \tag{17}$$

and

$$\frac{\partial \omega_{tr}}{\partial v_{trH}} \frac{v_{trH}}{\omega_{tr}} \equiv \varepsilon_{trH}^{\omega} = \left[\beta_1 + \beta_2 \frac{v_{trL}}{v_{trH}} + \beta_3 \left(\frac{v_{trA}}{l_{tr}} \right)^{\lambda_3} \right] \cdot \frac{v_{trH}}{v_{trA}} . \tag{18}$$

The terms outside the brackets are the vehicle categories' respective "market" (traffic) shares. The elasticities depend on these shares in a multiplicative fashion, as is commonly also found in travel demand analysis.

Combining these formulas with equation (6) of section 2, we note that the traffic shares cancel out, *leaving us with the terms inside the brackets as the most relevant measures in relation to externality assessments*. In plain language, we need to compute the *elasticity of accident frequency with respect to vehicle kilometres, times the inverse traffic share of each vehicle class*.

A.3. Estimation results

Main estimation results are presented in table 2.

In the main (*injury accidents*) model, the coefficient (β_1) of the overall traffic volume is estimated at 0.911. This coefficient has an interpretation as the partial effect of an additional road user, given a *constant mix between light and heavy vehicle traffic*, and given a *constant traffic density*.

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[12] Light vehicles are defined as all vehicles with less than 20 passenger seats or less than 1 tonne's carrying capacity.

It would, in other words, coincide with the elasticity with respect to the traffic volume only in the hypothetical case where the road network is extended at a rate corresponding to the traffic growth, so that the ratio of vehicle kilometres to road kilometres (the ADT) remains unchanged. Under these circumstances, the injury accident toll can be expected to increase almost proportionately with the overall traffic volume.

For the opposite and more realistic case, where the road network does not change, one has to combine the partial effects of traffic volume and traffic density (as in formula 14).

Table 2: Partial results from injury accident regression models. Parameter estimates, with t-statistics in parentheses. Source: Fridstrøm (1999)

Independent variable	Parameter	Dependent variable: Injury accidents in total	Pedestrian injuries	Single vehicle injury accidents	Multiple vehicle injury accidents
Overall traffic volume (vehicle kilometres)	β_1	0.911 (28.26)	1.109 (14.07)	0.804 (15.95)	1.032 (24.71)
Heavy vehicle share of traffic volume	β_2	0.149 (2.65)	0.105 (0.80)	-0.209 (-2.18)	0.347 (4.61)
Traffic density (vehicle kms per road km)	β_3	-0.435 (-11.02)	-0.927 (-10.66)	-0.081 (-5.30)	-0.569 (-6.88)
	λ_3	-0.013 (-0.17)	0.014 (0.22)	0.408 (2.40)	-0.165 (-1.11)
MC exposure proxy	β_4	0.027 (4.80)	0.036 (3.29)	0.032 (3.14)	0.028 (3.47)
Public bus service density	β_5	0.243 (8.02)	0.764 (10.86)	0.307 (6.50)	0.108 (2.66)
Light rail service density	β_6	0.019 (3.05)	0.065 (5.47)	-0.018 (-1.89)	0.025 (3.39)

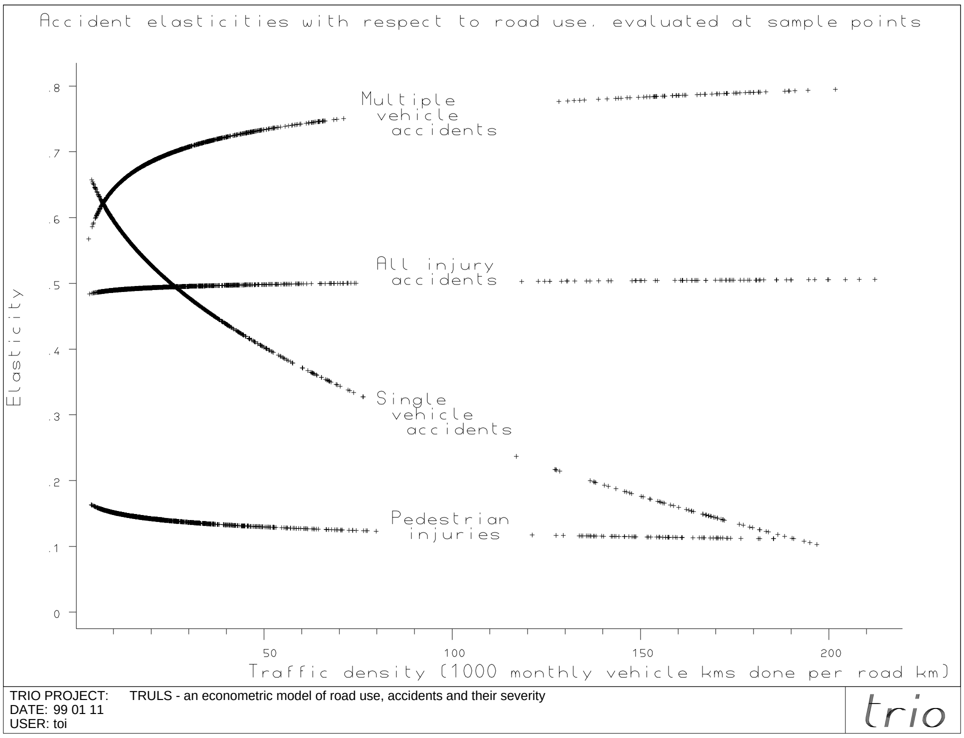

Figure 4: Accident elasticities with respect traffic volume, evaluated at sample points and plotted against traffic density.

The traffic density variable comes out with a slope coefficient of –0.435 and a curvature parameter of almost exactly zero. The latter corresponds, roughly speaking, to a logarithmic law, implying an almost constant elasticity irrespective of the density level (by formula 15).

Similar regression equations were also estimated for the number of *pedestrian injuries*, the number of *single vehicle* injury accidents, and the number of *multiple vehicle* injury accidents. They all show a close-to-unity coefficient (β_1) on the overall traffic volume and a negative coefficient (β_3) on the density factor. The curvature parameter (λ_3) is significantly different from zero only in the single vehicle accident equation. In this case it is positive, implying, since β_3 is negative, that the elasticity decreases with the density of traffic (formula 15).

In Figure 4, we exhibit – for each of the four equations – accident elasticities with respect to vehicle kilometres, *as evaluated at each sample point* and plotted against traffic density.

The general injury accident elasticity is estimated at approximately 0.5 for all sample points. For pedestrian injuries, the mean elasticity with respect to motorised traffic is only 0.14.

As we distinguish between single and multiple vehicle accidents, small traces of the "quadratic law" effect may seem to appear. For multiple vehicle accidents, the elasticity is as large as 0.71 as evaluated at the sample mean. It is slightly increasing with the traffic density, although this tendency is not statistically significant.

Single vehicle accidents, on the other hand, exhibit an elasticity of only 0.48 at the sample mean, and no more than 0.14 at the highest levels of traffic density.

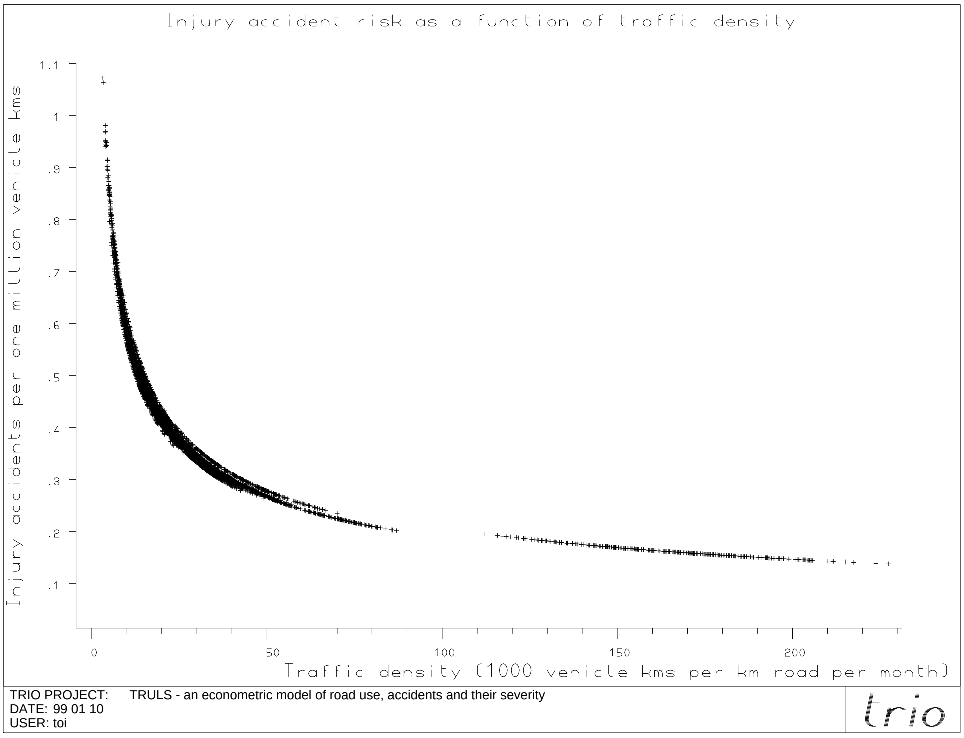

Figure 5: The partial relationship between injury accident risk and traffic density. Sample points from 19 counties 1974-94.

A.4. Interpretation in terms of risk

The less-than-unity elasticity of accidents with respect to road use translates into a negative *risk* elasticity $\varepsilon_A^r = \varepsilon_A^\omega - 1$. In Figure 5 we show – for all sample points – calculated injury accident risk measures (accidents per one million vehicle kilometres) plotted against traffic density, assuming an unchanging road network (like that of January 1980) in each county, and average values on all independent variables except motor vehicle road use.

The imputed risk varies by a factor of about seven between the highest and lowest density observations in the sample.

A.5. Discussion and suggestions for further research

We have been able to estimate the marginal effects of road use and traffic density on accidents and risk, thanks (i) to our Box-Cox regression model, which – rather than *imposing* a particular functional form on the data – allows the data to determine it, and (ii) to our combined cross-section/time-series data set, which allows us to identify the separate effects of traffic *volume* and traffic *density* and estimate them with considerable precision. In a pure time-series data set, these two variables would be almost perfectly collinear and, at best, provide only relatively imprecise estimates.

One might, however, want to ask to what extent these results could be generalised outside our sample. In general, the traffic density in Norway is relatively low by European standards. In our data set, only the county of Oslo exhibits traffic density levels above 90 000 vehicles per month, corresponding to an ADT of some 3 000 vehicles as averaged over all road links in the network. The maximum density represented in the sample corresponds to an ADT of approximately 7 000 vehicles.

Note, however, that these figures are not comparable to the traffic flow on given road links; they are interpretable as averages for all road links within an extended geographic area. Still we suspect that in most urbanised districts of, e g, Western Europe, the level of traffic density would often extend far beyond the values found in our Norwegian sample. A similar empirical analysis based on data from these regions would be necessary in order to assess whether the negative relationship between risk and density would hold even at the high rates of road use characterising the densely populated regions of Europe. One can only speculate if and how the apparently hyperbolic relationship shown in Figure 4 would extrapolate into the heavily congested domain.

In extending this line of reasoning, one may identify four rather intriguing questions, worthy of further research:

(i) Are we approaching the stage at which the accident externality cost generated by the marginal road user is zero or perhaps even negative, on account of the marginal road user's contribution to congestion and hence to speed limitation?

(ii) Or are we, perhaps, in some heavily congested regions even at a stage where the *total marginal accident cost* (external *and* internal) of road use is approaching zero?

(iii) Is this (one of) the reason(s) why accident counts in Western Europe generally have kept falling since the early 1970s, in spite of increasing road use?

(iv) Is there, perhaps, some kind of trade-off between congestion and accident externalities, the sum of the two being less variable than either, since congestion tends to reduce accidents and/or their severity? If such a "substitutability" between externalities exists, it has important implications for policy. Efforts to relieve congestion may entail not nearly the same social benefit as if these two externalities were not related – in certain cases perhaps no benefit at all.

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