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# The non-linearity of risk and the promotion of environmentally sustainable transport

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ABSTRACT

Several studies show that the risks of injury to pedestrians and cyclists are highly non-linear. This means that the more pedestrians or cyclists there are, the lower is the risk faced by each pedestrian or cyclist. On the other hand, the more motor vehicles there are, the higher becomes the risk faced by each pedestrian or cyclist. The relationships found in previous studies suggest that if very large transfers of trips from motor vehicles to walking or cycling take place, the total number of accidents may be reduced. The "safety in numbers" effect for pedestrians and cyclists would then combine favourably with the effect of a lower number of motor vehicles to produce a lower total number of accidents. This paper explores if such an effect is possible, relying on the findings of studies that show the non-linearity of injury risks for pedestrians and cyclists. It is found that for very large transfers of trips from motor vehicles to walking or cycling, a reduction of the total number of accidents is indeed possible. This shows that the high injury rate for pedestrians and cyclists in the current transport system does not necessarily imply that encouraging walking or cycling rather than driving will lead to more accidents.



## 1. Introduction

Increasing concern about global warming and environmental degradation has lead to a heightened interest in how best to promote environmentally sustainable transport. While the amount and forms of motorised transport that can be regarded as environmentally sustainable remains a topic for discussion, hardly anyone would dispute a claim that walking or cycling are environmentally sustainable modes of transport. Walking or cycling does not pollute, requires much less space than any form of motorised transport, and is associated with public health benefits. One way of promoting environmentally sustainable transport would therefore be to encourage walking and cycling, in particular if more walking or cycling is associated with a corresponding reduction in the use of motorised transport.

However, concerns about road safety would seem to represent an important argument against encouraging walking or cycling. These modes of transport are associated with a considerably higher risk of injury accidents than travel by car or bus. Fig. 1 shows injury rates per million kilometres of travel for Norway for various modes of travel during 1998–2005 (Bjørnskau, 2003, 2008; Rideng and Vågane, 2008). These injury rates are based on police reported injury accidents and estimates of the amount of travel based on travel behaviour surveys. The pattern seen in Fig. 1 is typical of many highly motorised countries. It is seen that the risk of injury when walking is about 4 times higher than when driving a car. The risk of injury when cycling is about 7.5 times higher than for car occupants. If more people walk or cycle, one would therefore, all else equal, expect there to be more injuries.

It is essential to keep in mind that the differences in injury risk shown in Fig. 1 represent the current modal split between the various modes of transport. Risks are not necessarily constant if modal split changes—if, for example, more people walk or cycle and fewer people drive. An increasing number of studies, reviewed in the next section, show that the risks of injury to pedestrians or cyclists are highly non-linear. The non-linearity of risk implies that, all else equal: (1) the more pedestrians or cyclists there are, the lower becomes the risk to each pedestrian or cyclist, and (2) the more motor vehicles there are, the higher becomes the risk to each pedestrian or cyclist. Hence, pedestrians or cyclists face a high risk if they are few in number and mix with a high number of motor vehicles. On the other hand, if pedestrians or cyclists are more numerous, and there are fewer motor vehicles, the risks faced by pedestrians or cyclists are comparatively low. This suggests that by getting car drivers to walk or cycle, walking or cycling would become safer and there would not necessarily be an increase in the number of road traffic injuries proportional to current levels of risk.

In fact, depending on the shape of the non-linearity of risk, it is even conceivable that a large transfer of trips from motor vehicles to walking or cycling would be associated with a reduction of the

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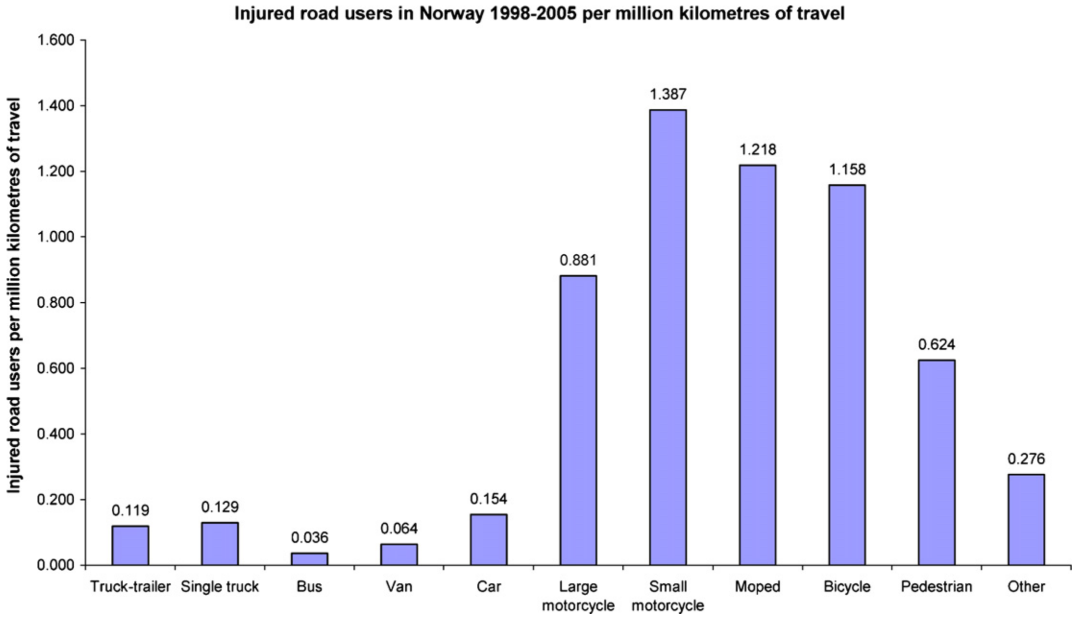


**Fig. 1.** Injured road users per million kilometres of travel in Norway 1998–2005. Sources: see text.

number of accidents. The main objectives of this paper are: (1) to explore if such an outcome is possible and (2) gain an impression of the size of the transfer of trips from motor vehicles to walking or cycling that is needed in order to pass the "tipping point" at which the combined benefits of "safety in numbers" for pedestrians or cyclists and a reduced number of motor vehicles lead to fewer accidents.

## 2. Literature review

A number of recent studies have shown that the risks of injury to pedestrians or cyclists are non-linear, that is they depend on the number of pedestrians or cyclists. All these studies have found that the risk faced by each pedestrian or cyclist declines as the number of pedestrians or cyclists increases. This has been labelled the "safety in numbers" effect. Table 1 reviews recent studies that have found a "safety in numbers" effect for pedestrians or cyclists.

The studies listed in Table 1 are those that have been quoted most frequently in recent years. No claim is made that the studies included in Table 1 are exhaustive. For the purpose of this paper, however, it is not essential that the studies reviewed are all those that have ever been made. Should it be the case that the list of studies in Table 1 is incomplete, and the missing studies have produced findings suggesting that there is no safety in numbers effect, it would be easy to revise the simple model estimates developed in this paper.

Most of the studies listed in Table 1 have developed accident prediction models for pedestrian or bicyclist accidents of the following general form:

$$\text{Number of accidents} = \alpha Q_{MV}^{\beta_1} Q_{PED}^{\beta_2} \tag{1}$$

In this equation, $Q_{MV}$ and $Q_{PED}$ represent the volume of motor vehicles and the volume of pedestrians ($Q_{CYC}$ is the volume of cyclists), often indicated by the annual average daily traffic (AADT), $\alpha$, $\beta_1$ and $\beta_2$ are coefficients that are estimated. The coefficient $\alpha$ is a scaling parameter, which ensures that the predicted number of accidents is in the same range as the recorded number of accidents. Coefficients $\beta_1$ and $\beta_2$ describe the shape of the relationship between traffic volume and the number of accidents. As shown by the studies listed in Table 1, either coefficient often takes on a value between about 0.3 and 0.9. The sum of the two coefficients tends to be greater than 1. Briefly speaking, this means that: (1) the risk to each pedestrian or cyclist declines as the number of pedestrians or cyclists increases, (2) the risk to each motorist of striking a pedestrian or cyclist declines as the number of motor vehicles increases, and (3) the risk to each pedestrian or cyclist increases as the number of motor vehicles increases. This suggests that if there is a large transfer of trips from motor vehicles to walking or cycling, it is in principle conceivable that the number of accidents could decline.

## 3. Model estimates of the expected number of accidents

### 3.1. Exploratory analysis of model parameters

Based on the studies shown in Table 1, an exploratory analysis has been performed for the purpose of determining whether certain transfers of trips from motor vehicles to walking or cycling are associated with a reduction in the total number of accidents. The total number of accidents includes not just accidents involving pedestrians or cyclists, but also accidents involving motor vehicles only. To model the relationship between the number of motor vehicles and accidents involving motor vehicles only, recent accident models (Fridstrøm, 1999; Taylor et al., 2002) and reviews of such models (Eenink et al., 2007; Reurings et al., 2006) were studied. The shape of the relationship between the number of motor vehicles and the number of accidents varies depending on the type of accident. Broadly speaking, a distinction can be made between multi-vehicle accidents (rear-end, head-on, junction accidents) and single-vehicle accidents. The following functional relationships were chosen for these accidents:

$$\text{Multi-vehicle motor vehicle accidents} = \alpha Q_{MV}^{1.05} \tag{2}$$

$$\text{Single-vehicle motor vehicle accidents} = \alpha Q_{MV}^{0.80} \tag{3}$$

The relationship in Eq. (2) implies that the number of multi-vehicle accidents involving motor vehicles only increases slightly more than proportional to the number of motor vehicles. The relationship in Eq. (3) implies that the number of single-vehicle accidents involving motor vehicles only increases less than proportional to the number of motor vehicles. It is assumed that the total number of accidents is equal to the sum of multi-vehicle motor vehicle accidents, single vehicle motor vehicle accidents, accidents

**Table 1**
Studies that evaluated the non-linearity of the risks faced by pedestrians and cyclists.

| Authors | Year | Country | Study units | Sample size | Number of accidents | Type of accident | Measure of exposure | Exponent | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Motor vehicles | Pedestrians | Cyclists |
| Brüde, Larsson | 1993 | Sweden | Junctions | 285 | 165 | Pedestrian | Entering motor vehicles, crossing pedestrians | 0.50 | 0.72 | |
| Brüde, Larsson | 1993 | Sweden | Junctions | 377 | 432 | Cyclist | Entering motor vehicles, entering cyclists | 0.52 | | 0.65 |
| Leden, Gårder, Pulkkinen | 1998 | Sweden | Junctions | | 276 | Cyclist | Entering cyclists | | | 0.47 |
| Leden | 2002 | Canada | Junctions | 749 | 39 | Pedestrian | Right turning motor vehicles, crossing pedestrians | 0.86 | 0.48 | |
| Leden | 2002 | Canada | Junctions | 126 | 27 | Pedestrian | Left turning motor vehicles, crossing pedestrians | 1.19 | 0.33 | |
| Lyon, Persaud | 2002 | Canada | Junctions | 684 | 5280 | Pedestrian | Entering motor vehicles, entering pedestrians | 0.57 | 0.74 | |
| Lyon, Persaud | 2002 | Canada | Junctions | 263 | 1065 | Pedestrian | Entering motor vehicles, entering pedestrians | 0.40 | 0.41 | |
| Lyon, Persaud | 2002 | Canada | Junctions | 122 | 159 | Pedestrian | Entering motor vehicles, entering pedestrians | 0.53 | 0.66 | |
| Lyon, Persaud | 2002 | Canada | Junctions | 123 | 319 | Pedestrian | Entering motor vehicles, entering pedestrians | 0.58 | 0.71 | |
| Jacobsen | 2003 | United States | Cities | 68 | | Pedestrian | Share of working trips on foot | | 0.41 | |
| Jacobsen | 2003 | United States | Cities | 68 | | Cyclist | Share of working trips on bicycle | | | 0.31 |
| Jacobsen | 2003 | Denmark | Towns | 47 | | Pedestrian | Kilometres walked per inhabitant per day | | 0.36 | |
| Jacobsen | 2003 | Denmark | Towns | 47 | | Cyclist | Kilometres cycled per inhabitant per day | | | 0.44 |
| Jacobsen | 2003 | 14 European | Country | 14 | | Cyclist | Kilometres cycled per inhabitant per day | | | 0.58 |
| Jacobsen | 2003 | 8 European | Country | 8 | | Pedestrian | Trips on foot per inhabitant per day | | 0.13 | |
| Jacobsen | 2003 | 8 European | Country | 8 | | Cyclist | Trips on bicycle per inhabitant per day | | | 0.48 |
| Robinson[a] | 2005 | Australia | States | 7 | | Cyclist | Kilometres cycled per inhabitant per day | | | 0.52 |
| Jonsson | 2005 | Sweden | Road sections | 393 | 130 | Pedestrian | Motor vehicle kilometres, pedestrians crossing and walking along road | 0.83 | 0.38 | |
| Jonsson | 2005 | Sweden | Road sections | 393 | 343 | Cyclist | Motor vehicle kilometres, cyclists crossing and riding along road | 0.76 | | 0.35 |
| Geyer et al. | 2006 | Oakland | Junctions | 247 | 185 | Pedestrian | Entering motor vehicles, crossing pedestrians | 0.16 | 0.61 | |
| Harwood et al. | 2008 | United States | Junctions | 450 | 728 | Pedestrian | Entering motor vehicles, entering pedestrians | 0.05 | 0.41 | |
| Harwood et al. | 2008 | United States | Junctions | 1433 | 4824 | Pedestrian | Entering motor vehicles, entering pedestrians | 0.40 | 0.45 | |
| | | | | | | | Mean (simple) | 0.57 | 0.50 | 0.48 |
| | | | | | | | Median (simple) | 0.53 | 0.43 | 0.48 |
| | | | | | | | Weighted (by accidents) mean (pedestrians) | 0.46 | 0.58 | |
| | | | | | | | Weighted (by accidents) mean (cyclists) | 0.63 | | 0.50 |

[a] One outlying data point omitted from the study of Robinson.

in which a pedestrian is struck by a motor vehicle and accidents in which a cyclist is struck by a motor vehicle. The following parameters were varied:

1. Number of motor vehicles.
2. Number of pedestrians.
3. Number of cyclists.
4. Coefficient values for pedestrian or bicyclist accidents.

As far as the number of motor vehicles was concerned, initial AADT-values of 2000, 3000, 5000, 7500, 10,000, 15,000, 20,000, 25,000 and 30,000 were used. A single initial value of 200 pedestrians per day was used, irrespective of the number of motor vehicles. A single initial value of 100 bicyclists per day was used, irrespective of the number of motor vehicles. The number of pedestrian or bicyclist accidents was predicted by applying a model identical in its form to Eq. (1). The initial values of the coefficients were 0.7 for motor vehicles and 0.4 for pedestrians in the equation predicting pedestrian accidents, and 0.7 for motor vehicles and 0.5 for bicyclists in the equation predicting bicyclist accidents.

No distinction was made between different modes of motorised travel, such as car, bus, tram or motorcycle. However, as shown in Fig. 1, different modes of motorised travel have very different average injury rates. One would therefore expect a transfer of trips from a comparatively risky mode, like moped, to have a different effect on safety than a transfer of trips from a comparatively safe mode of travel, like bus. Unfortunately, the shape of the relationship between the number of accidents and the volume of traffic for a specific mode of motorised travel is not known. Available accident prediction models only refer to motorised travel in general, not specifying the mode.

The extent to which the models included in Table 1 have controlled for the effects of other variables influencing the number of pedestrian and cyclist accidents varies. An extensive study reported by Harwood et al. (2008) suggests that the shape of the relationship between the number of accidents and the volume of vehicular and pedestrian traffic is not altered when other variables are included in a model, like the proximity to a school, the presence of a bus stop or the presence of an alcohol sales establishment. Jonsson (2005) also tested several accident prediction models and found the coefficients representing pedestrian or cyclist volume to be stable across the different model specifications. The coefficients listed in Table 1 have therefore been assumed to apply in general, although it is clear that the number of pedestrian or cyclist accidents will be influenced by a host of other variables not specified in Table 1.

Denote by MVA a motor vehicle accident involving more than one vehicle, by SVA an accident involving a single motor vehicle, by PA an accident in which a pedestrian is struck by a motor vehicle and by CA an accident in which a cyclist is struck by a motor vehicle. The model applying to the baseline situation had the following form:

$$\begin{aligned}\text{Number of accidents} &= \text{MVA} + \text{SVA} + \text{PA} + \text{CA} \\ &= \alpha_{\text{MVA}} Q_{\text{MV}}^{1.05} + \alpha_{\text{SVA}} Q_{\text{MV}}^{0.80} \\ &\quad + \alpha_{\text{PA}} Q_{\text{MV}}^{0.70} Q_{\text{PED}}^{0.40} + \alpha_{\text{CA}} Q_{\text{MV}}^{0.70} Q_{\text{CYC}}^{0.50}\end{aligned}$$

The effects on accidents of the following changes were estimated:

1. Doubling the number of pedestrians or cyclists. Corresponding reductions in the number of motor vehicles were assumed.
2. Reducing the number of motor vehicles by 25%, and increasing the number of pedestrians or cyclists correspondingly. It was assumed that 2/3 would be pedestrians, 1/3 cyclists.
3. Reducing the number of motor vehicles by 50%, and increasing the number of pedestrians or cyclists correspondingly. It was assumed that 2/3 would be pedestrians, 1/3 cyclists.
4. The same three changes, but assuming a parameter of 0.6 for motor vehicles, and 0.7 for both pedestrians and cyclists.
5. The same three changes, but assuming a parameter of 0.8 for motor vehicles, 0.3 for pedestrians and 0.4 for cyclists.
6. The same changes as in points 1–5, but assuming that 2/3 would be cyclists and 1/3 would be pedestrians.

### 3.2. Estimated effects on accidents of increased walking or cycling

Table 2 reports the results of the model estimations. If walking or cycling is doubled (point 1 above), there will be very small changes in the number of accidents. There will be a small reduction when the volume of motor vehicles is low, a small increase when the volume of motor vehicles is high. Reducing the number of motor vehicles by 25% (point 2 above) is associated with a reduction of the number of accidents at all volumes. The reduction is, however, very small at high traffic volumes. Reducing the number of motor vehicles by 50% (point 3 above) is associated with a reduction in the number of accidents throughout the range of traffic volume.

If the parameters are changed, as suggested in point 4 above, there is an increase in the number of accidents, irrespective of the size of the transfer of trips by motor vehicles to walking or cycling. Although pedestrians and cycling are protected by safety in numbers even in this scenario, the effect is too small to prevent an increase in the number of accidents. The only exceptions from this refer to transferring 50% of trips by motor vehicles to walking or cycling at low volumes of motor traffic.

Changing parameters to 0.8 for motor vehicles, 0.3 for pedestrians and 0.4 for cyclists (point 5 above) produces results that are almost identical to those obtained using the initial parameter values of 0.7, 0.4 and 0.5, respectively. What appears to have the greatest influence on the results is whether the values of the parameters for pedestrians or cyclists are lower than the value of the parameter for motor vehicles. As long as this is the case, the safety in numbers effect kicks in with full force. However, if the values of the parameters for pedestrians or cyclists are greater than the value of the parameter for motor vehicles, the safety in numbers effect is too weak to prevent the number of accidents from increasing as the number of pedestrians and cyclists increases. Even if 50% of motor traffic is transferred to the non-motorised modes, motor vehicles remain more numerous than either pedestrians or cyclists (though not more numerous than the sum of pedestrians and cyclists).

The estimates presented above are representative of countries in which walking is the dominant mode of non-motorised transport. This applies to most highly motorised countries, but in a few countries, notably Denmark and the Netherlands, cycling is the dominant mode of non-motorised transport. The estimates were repeated, assuming that 2/3 of non-motorised travel is cycling, 1/3 walking. This did not influence the results very much. Given the uncertainty that is bound to be associated with these model estimates, the results were, for all intents and purposes, the same. It does not matter a great deal if the transfer of trips to non-motorised modes of transport favours walking or cycling.

## 4. Discussion

The model estimates presented above suggest that, if circumstances are favourable, transferring a substantial part of trips made by motor vehicles to walking or cycling may lead to fewer accidents. This is a highly counterintuitive finding, given the fact that walking or cycling involves a 5–10 times higher risk of injury per kilometre travelled than driving a car. The explanation of the surprising finding is the non-linearity of risk: the more people walk or

**Table 2**
Model estimates of changes in the expected number of accidents associated with transferring motorised travel to walking or cycling.

| Traffic volume (per day) | | | | Relative number of accidents | Relative change in number of accidents | | |
|---|---|---|---|---|---|---|---|
| Motor vehicles | Pedestrians | Cyclists | Total | | Parameters 0.7 (mv); 0.4 (ped); 0.5 (cycl) | Parameters 0.6 (mv); 0.7 (ped); 0.7 (cycl) | Parameters 0.8 (mv); 0.3 (ped); 0.4 (cycl) |
| 2000 | 200 | 100 | 2300 | 1.00 | | | |
| 3000 | 200 | 100 | 3300 | 1.47 | | | |
| 5000 | 200 | 100 | 5300 | 2.40 | | | |
| 7500 | 200 | 100 | 7800 | 3.56 | | | |
| 10,000 | 200 | 100 | 10300 | 4.72 | | | |
| 15,000 | 200 | 100 | 15300 | 7.02 | | | |
| 20,000 | 200 | 100 | 20300 | 9.33 | | | |
| 25,000 | 200 | 100 | 25300 | 11.64 | | | |
| 30,000 | 200 | 100 | 30300 | 13.95 | | | |
| Doubling number of pedestrians or cyclists; corresponding reduction of number of motor vehicles | | | | | | | |
| 1700 | 400 | 200 | 2300 | | 0.914 | 1.018 | 0.908 |
| 2700 | 400 | 200 | 3300 | | 0.958 | 1.049 | 0.955 |
| 4700 | 400 | 200 | 5300 | | 0.990 | 1.067 | 0.991 |
| 7200 | 400 | 200 | 7800 | | 1.005 | 1.071 | 1.007 |
| 9700 | 400 | 200 | 10300 | | 1.011 | 1.070 | 1.015 |
| 14,700 | 400 | 200 | 15300 | | 1.017 | 1.067 | 1.022 |
| 19,700 | 400 | 200 | 20300 | | 1.019 | 1.063 | 1.025 |
| 24,700 | 400 | 200 | 25300 | | 1.020 | 1.060 | 1.026 |
| 29,700 | 400 | 200 | 30300 | | 1.020 | 1.057 | 1.027 |
| Reducing motor vehicles by 25%, corresponding increases in walking or cycling | | | | | | | |
| 1500 | 530 | 270 | 2300 | | 0.842 | 0.999 | 0.831 |
| 2250 | 700 | 350 | 3300 | | 0.858 | 1.054 | 0.848 |
| 3750 | 1030 | 520 | 5300 | | 0.882 | 1.136 | 0.873 |
| 5625 | 1450 | 725 | 7800 | | 0.902 | 1.213 | 0.895 |
| 7500 | 1860 | 940 | 10300 | | 0.918 | 1.274 | 0.912 |
| 11,250 | 2700 | 1350 | 15300 | | 0.940 | 1.368 | 0.937 |
| 15,000 | 3530 | 1770 | 20300 | | 0.957 | 1.442 | 0.956 |
| 18,750 | 4360 | 2190 | 25300 | | 0.970 | 1.503 | 0.971 |
| 22,500 | 5200 | 2600 | 30300 | | 0.981 | 1.555 | 0.984 |
| Reducing motor vehicles by 50%, corresponding increases in walking or cycling | | | | | | | |
| 1000 | 870 | 430 | 2300 | | 0.621 | 0.863 | 0.601 |
| 1500 | 1200 | 600 | 3300 | | 0.639 | 0.933 | 0.617 |
| 2500 | 1870 | 930 | 5300 | | 0.662 | 1.038 | 0.640 |
| 3750 | 2700 | 1350 | 7800 | | 0.682 | 1.134 | 0.661 |
| 5000 | 3530 | 1770 | 10300 | | 0.697 | 1.209 | 0.676 |
| 7500 | 5200 | 2600 | 15300 | | 0.718 | 1.326 | 0.698 |
| 10,000 | 6870 | 3430 | 20300 | | 0.734 | 1.418 | 0.714 |
| 12,500 | 8530 | 4270 | 25300 | | 0.747 | 1.493 | 0.728 |
| 15,000 | 10200 | 5100 | 30300 | | 0.757 | 1.558 | 0.739 |
| 2000 | 100 | 200 | 2300 | 1.00 | | | |
| 3000 | 100 | 200 | 3300 | 1.47 | | | |
| 5000 | 100 | 200 | 5300 | 2.40 | | | |
| 7500 | 100 | 200 | 7800 | 3.55 | | | |
| 10,000 | 100 | 200 | 10300 | 4.69 | | | |
| 15,000 | 100 | 200 | 15300 | 6.98 | | | |
| 20,000 | 100 | 200 | 20300 | 9.27 | | | |
| 25,000 | 100 | 200 | 25300 | 11.56 | | | |
| 30,000 | 100 | 200 | 30300 | 13.85 | | | |
| Doubling number of pedestrians or cyclists; corresponding reduction of number of motor vehicles | | | | | | | |
| 1700 | 200 | 400 | 2300 | | 0.921 | 1.011 | 0.914 |
| 2700 | 200 | 400 | 3300 | | 0.964 | 1.043 | 0.960 |
| 4700 | 200 | 400 | 5300 | | 0.996 | 1.061 | 0.995 |
| 7200 | 200 | 400 | 7800 | | 1.010 | 1.066 | 1.012 |
| 9700 | 200 | 400 | 10300 | | 1.016 | 1.066 | 1.019 |
| 14,700 | 200 | 400 | 15300 | | 1.021 | 1.063 | 1.026 |
| 19,700 | 200 | 400 | 20300 | | 1.023 | 1.059 | 1.029 |
| 24,700 | 200 | 400 | 25300 | | 1.024 | 1.057 | 1.030 |
| 29,700 | 200 | 400 | 30300 | | 1.024 | 1.054 | 1.030 |
| Reducing motor vehicles by 25%, corresponding increases in walking or cycling | | | | | | | |
| 1500 | 270 | 530 | 2300 | | 0.850 | 0.989 | 0.837 |
| 2250 | 350 | 700 | 3300 | | 0.869 | 1.041 | 0.857 |
| 3750 | 520 | 1030 | 5300 | | 0.896 | 1.119 | 0.885 |
| 5625 | 725 | 1450 | 7800 | | 0.920 | 1.192 | 0.910 |
| 7500 | 940 | 1860 | 10300 | | 0.938 | 1.250 | 0.929 |
| 11,250 | 1350 | 2700 | 15300 | | 0.965 | 1.338 | 0.958 |
| 15,000 | 1770 | 3530 | 20300 | | 0.984 | 1.408 | 0.980 |
| 18,750 | 2190 | 4360 | 25300 | | 1.000 | 1.465 | 0.997 |

Table 2 (*Continued* )

| Traffic volume (per day) | | | | Relative number of accidents | Relative change in number of accidents | | |
|---|---|---|---|---|---|---|---|
| Motor vehicles | Pedestrians | Cyclists | Total | | Parameters 0.7 (mv); 0.4 (ped); 0.5 (cycl) | Parameters 0.6 (mv); 0.7 (ped); 0.7 (cycl) | Parameters 0.8 (mv); 0.3 (ped); 0.4 (cycl) |
| 22,500 | 2600 | 5200 | 30300 | | 1.013 | 1.515 | 1.011 |
| Reducing motor vehicles by 50%, corresponding increases in walking or cycling | | | | | | | |
| 1000 | 430 | 870 | 2300 | | 0.634 | 0.848 | 0.610 |
| 1500 | 600 | 1200 | 3300 | | 0.654 | 0.915 | 0.628 |
| 2500 | 930 | 1870 | 5300 | | 0.681 | 1.013 | 0.655 |
| 3750 | 1350 | 2700 | 7800 | | 0.705 | 1.104 | 0.678 |
| 5000 | 1770 | 3530 | 10300 | | 0.722 | 1.176 | 0.695 |
| 7500 | 2600 | 5200 | 15300 | | 0.748 | 1.286 | 0.721 |
| 10,000 | 3430 | 6870 | 20300 | | 0.767 | 1.372 | 0.740 |
| 12,500 | 4270 | 8530 | 25300 | | 0.782 | 1.444 | 0.755 |
| 15,000 | 5100 | 10200 | 30300 | | 0.795 | 1.505 | 0.768 |

cycle, the safer walking or cycling becomes. This is good news to all those who want to encourage walking or cycling in order to promote environmental sustainability, but who have so far been held back by concerns about the high injury risk of the non-motorised modes of travel.

There are, however, several caveats to be made about the model estimates presented in this paper. In the first place, accidents involving pedestrians or cyclists – in particular cyclists – are poorly reported in official road accident statistics (Elvik and Mysen, 1999). The injury risks associated with these modes of travel are in fact even higher than estimates based on official accident statistics suggest. It is not known if the safety in numbers effects applies to the non-reported accidents as well as to those reported in official statistics. A fairly high proportion of bicycle accidents not reported in official statistics are single-vehicle accidents, not involving any other road users. These accidents may not be subject to the safety in numbers effect. On the other hand, most of the non-reported accidents involve slight injury only. In a recent study, Veisten et al. (2007) estimated the reporting of bicycle injuries in Norway to about 27%, which is higher than older studies have indicated. Nearly all the non-reported injuries were slight (Abbreviated Injury Scale = 1). The mean societal cost of the non-reported injuries was considerably lower than for the reported injuries. Cost-benefit analyses suggest that even if the assumption is made that the number of unreported accidents increases in proportion to kilometres walked or cycled, the public health benefits of more walking or cycling remain larger than the increased costs of treating injuries (Sælensminde, 2004).

In the second place, the exact shape of the non-linearity of risk is not known. The early study of Brüde and Larsson (1993) was made in junctions that had a rather low number of pedestrians or cyclists. Although a safety in numbers effect was found, it was too weak to offset an increasing number of accidents if pedestrian or cyclist volume increased. The more recent study of Jonsson (2005), made in urban areas that had a higher volume of pedestrians or cyclists, suggests a far greater safety in numbers effect. It may therefore be too simple to model the effects on accidents of the number of motor vehicles and the number of non-motorised road users in terms of a single parameter estimate for each of the groups. Perhaps Box–Cox transformations are needed, allowing the parameter values to change as a function of the mix of motor vehicles, pedestrians and cyclists. The safety in numbers effect may become stronger as the number of pedestrians or cyclists increases.

In the third place, nothing is known about the effects of crowding on the number of accidents involving pedestrians or cyclists only (i.e. no motor vehicle involved). There have been reports in mass media about congestion on certain cycle tracks in Copenhagen. Once a large number of cyclists travel at a brisk pace, the risk of crashes between the cyclists is likely to increase. These crashes could turn into mass pile-ups, as anyone who has watched cycle races like the Tour-de-France on TV will know. Pedestrians are considerably more flexible in this respect than cyclists. A congested sidewalk slows all pedestrians down, but it does not generate injury accidents. To alleviate congestion, one could convert a street to a cycle street in which cyclists had the right-of-way in all driving lanes (a sidewalk reserved for pedestrians only might be retained). While motor vehicles would be permitted to enter, they would have to yield to cyclists. Clearly the low speed of motor vehicles implies a very low injury rate for motor vehicle occupants. On the other hand, the larger space available for cyclists could make even collisions between cyclists less likely.

In the fourth place, the transfer of trips to walking or cycling assumed in this paper may seem totally unrealistic. It is true that car drivers are an entrenched lot; it is not easy to convince them that walking or cycling is a better alternative. However, most trips by car are very short. According to the recent travel behaviour survey in Norway (Vågane, 2006), almost half of car trips are shorter than 5 km, a distance easily covered by cycling. Indeed, in congested city traffic, cycling may be the fastest mode of travel. About 18% of car trips were shorter than 2 km, a distance any healthy person can walk without problems. Walking will, of course, almost always be the slowest mode of travel, but it has other benefits. It gives you time to think, for example—surely a luxury in a world that increasingly expects everybody to be online at all times, always ready to be distracted by any request for their attention.

In the fifth place, it is in principle conceivable that the safety in numbers effect becomes insignificant when traffic is dominated by pedestrians and cyclists and there are very few motor vehicles, as is the case in some low-income countries. In these countries, the accident rate tends to be high and each car may represent a high risk, since there are few cars and pedestrians and cyclists are therefore not accustomed to interacting with cars. Moreover, in countries characterised by rapid motorisation, there may be a more intense rivalry between road user groups sharing the same space than in countries that have been motorised for a long time, as cars try to gain control of the space that used to be dominated by pedestrians and cyclists.

## 5. Conclusions

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

1. In the current transport system, pedestrians and cyclists are exposed to a considerably higher risk of injury accidents than motorists, in particular car drivers.

2. Several studies suggest that the risks faced by pedestrians and cyclists are highly non-linear. As the number of pedestrians or cyclists increases, the risk faced by each pedestrian or cyclist goes down.
3. By applying the results of studies that show the non-linearity of risk, a method was developed to show potential effects on accidents of transferring trips from motorised travel to walking or cycling. It was found that, in theory, the total number of accidents could go down if a substantial share of trips by motorised transport is transferred to walking or cycling.
4. The potential effects on accidents of transferring trips from motorised modes of travel to walking or cycling depend strongly on the degree of non-linearity of risk. The more nearly linear the risks faced by pedestrians or cyclists are, the more likely it is that increased walking or cycling will be associated with an increased number of accidents.
5. The model estimates presented in this paper are exploratory only and do not take account of accidents not reported in official accident statistics or of accidents involving pedestrians and/or cyclists only. Nothing is known about the shape of the relationship between the volume of pedestrians or cyclists and these types of accident.

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