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How can cyclist injuries be included in health impact economic assessments?

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ABSTRACT

This paper discusses how injuries sustained while cycling can be included as a component of health impact assessments of increased cycling. To include injuries as a component of a health impact assessment, their expected frequency of occurrence and impacts on health must be well known. In this respect, incomplete reporting of cyclist injuries in official accident statistics is an obstacle for good health impact assessment. It is convenient to represent injuries in terms of an expected loss of health per cyclist or kilometre cycled, which can be converted to monetary terms to make it comparable with the health benefits. It is suggested that stating health loss in terms of DALYs (Disability Adjusted Life Years) is suitable for this purpose. Examples are given of how to estimate the health loss associated with bicycle injuries. It is more difficult to model the probability of injury. Two approaches are compared. One approach relies on the relationship between distance cycled per year and risk of injury. The other approach is based on the concept of safety-in-numbers. The number of injuries is modelled as a function of the number of cyclists and motor vehicles. Results are found to be greatly influenced by the assumptions made about the share of increased cycling that comes from a modal shift from motor vehicles.

Key words: cycling; injuries; disability weights; monetary valuation; health impact assessment

1 BACKGROUND AND RESEARCH PROBLEM

It is an objective of transport policy in many countries to encourage more physically active transport by means of walking or cycling. If motorised travel is replaced by walking or cycling, there may be benefits in terms of less traffic congestion, less pollution (including the contribution to global warming) and improved public health. However, it is difficult to estimate the expected effects of an increase in walking or cycling. One of the problems encountered is that official accident statistics, which is usually the most easily accessible source of data about traffic injuries, tends to be very incomplete with respect to cyclist injuries. A recent study in Oslo, Norway (Elvik 2017A) compared cyclist injuries recorded by the police in 2014 to injuries recorded as part of a research project carried out by the municipal emergency medical clinic (Oslo legevakt). The overall level of reporting in police statistics was found to be 7.5 %. The reporting of slight injuries sustained in single bicycle crashes was particularly low: 0.4 %. It is clear that relying on such an incomplete source of data can give highly misleading results concerning the impact of increased cycling on the number of cyclist injuries. Another challenge is how best to model the relationship between the amount of cycling (and walking) and the number of injuries.

Many studies (see Elvik and Bjørnskau 2017 for a review) suggest that the relationship is not linear and that the number of injuries does not increase in proportion to the amount of cycling, a phenomenon referred to as safety-in-numbers.

The objective of this paper is to discuss how the risk of injury when cycling can be included in health impact assessments. The main research problems of this paper are:

1. What is known about the health impacts of injuries sustained by cyclists? Can health impacts be summarised by means of a generic indicator such as DALYs (Disability Adjusted Life Years)?
2. What is known about the risk of injury per cyclist or per kilometre cycled? Is non-linearity of risk (safety-in-numbers) sufficiently known to account for it in health impact modelling?

To answer these questions, mostly Norwegian data, but also some Swedish data will be used. Before presenting and discussing these data, relevant previous studies will be reviewed.

2 REVIEW OF HEALTH IMPACT ASSESSMENTS OF WALKING AND CYCLING

Many health impact assessments of increased walking and cycling have been reported in the literature, see Mueller et al. (2015) for a review. Table 1 lists some of the health impact assessments in chronological order (Woodcock et al. 2009, Rabl and de Nazelle 2012, Woodcock et al. 2013, Maizlich et al. 2013, Rojas-Rueda et al. 2013, Woodcock et al. 2014, Schepers et al. 2015, Rojas-Rueda et al. 2016, Nilsson et al. 2017, Maizlich et al. 2017).

Table 1 about here

The most common scenario in these health impact assessments is an increase in walking and cycling. Most studies assume that all or most of the increase in walking or cycling will be associated with a corresponding reduction in car driving. Disability Adjusted Life Years (DALYs) in the most frequently used estimator of health impacts. The first studies did not consider safety-in-numbers, but this is done in most of the recent studies. In the first of the studies listed in Table 1 to consider the safety-in-numbers effect (Woodcock et al. 2013), the estimated number of traffic injuries was reduced when a safety-in-numbers effect was assumed, but increased when no such effect was assumed. An appropriate modelling of safety-in-numbers may therefore influence the results of a health impact assessment.

Most health impact assessments find that the benefits exceed the costs, but the health impact assessment of the London bicycle sharing system (Woodcock et al. 2014) found that injuries sustained by women almost made up for the health gains (when both gains and losses were stated in terms of DALYs). In principle, therefore, health losses attributable to injuries may represent a significant disadvantage of cycling.

The health impact assessments listed in Table 1 are rather brief in describing the sources of data. It would seem, however, that they mostly rely on official accident statistics, which, as noted above, is very incomplete with respect to cyclist injuries. It is thus of some interest to explore the use of a data source that can reasonably be treated as more complete than statistics based on police reports. The studies listed in Table 1 are inconsistent in their conclusions about changes in the number of traffic injuries, with some studies concluding that the number of injuries will increase, other studies concluding the opposite.

3 A DEDICATED DATA SET ABOUT BICYCLE INJURIES

The first problem encountered when trying to estimate the health impacts of cyclist injuries is that the reporting of these injuries is very incomplete in official accident statistics (Elvik and Mysen 1999, Amoros et al. 2006). A dedicated system for recording cyclist injuries was set up in Oslo, Norway, during 2014 at the medical emergency clinic (Melhuus et al. 2015). This clinic is open all day. Almost all users of the facility come there on their own for treatment of injuries that require medical attention but are not serious enough to require admittance to hospital. Nearly all injuries are treated immediately and victims go home again the same day. More seriously injured cyclists may be transported directly to hospital, without going to the emergency centre. Cyclist injuries were recorded systematically in 2014 as part of a research project, and 2184 injury victims were recorded in total. This includes 46 cyclists who were transported directly to hospital.

A similar source of data exists in Sweden, the STRADA system. In the STRADA system, traffic injuries are recorded by hospitals. STRADA includes both injury victims who are treated as out-patients (comparable to those recorded in Oslo in 2014) and those who are admitted to hospital. Data on injured cyclists recorded in STRADA were recently presented in a paper by Nilsson et al. (2017). The data collected in Oslo in 2014 and the STRADA data given by Nilsson et al. (2017) are used in this paper to illustrate how one may estimate the health losses associated with cyclist injuries.

4 MEASURING HEALTH LOSSES ASSOCIATED WITH INJURIES

Injured cyclists in Oslo were diagnosed according the ICD-10 system (International Classification of Diseases, tenth revision). Diagnoses belonging to the same group according to the first two digits were grouped. The resulting set of diagnoses is shown in Table 2. A total of 2184 injured cyclists were recorded, but injuries with impacts that could be assessed by the Eurocost health assessment tool (Haagsma et al. 2012) were known only for 2128 cyclists.

Table 2 about here

4.1 Two sets of disability weights

The impacts of injuries have been described by disability weights. A disability weight provides a generic description of health and takes on values between 0 (no disability = normal function) and 1 (death = no bodily function). The greater the value of a disability weight, the greater the degree of disability. Two sets of disability weights have been applied. The first and most detailed set is the Eurocost system, developed by Haagsma et al. (2012). It provides disability weights for 39 different injuries. For each injury, a probability that it may be lifelong is given. For lifelong injuries, a separate set of disability weights has been developed. The disability weights for temporary injuries refer to a period of one year.

The second set of disability weights was developed by the World Health Organization for the global burden of disease study (WHO 2004). There are two sets of disability weights; one set refers to temporary injuries, the other to lifelong injuries. For the injury weights referring to temporary injuries, each weight has been multiplied by the duration of the disability, relying on a study by Tainio et al. (2014). The duration of the disability associated with temporary injuries is stated by Nilsson et al. (2017).

Table 2 shows that almost all injuries recorded by the emergency centre in Oslo in 2014 were temporary. Only about 1.2 % of injured cyclists sustained an injury that might lead to a lifelong disability. According to the Eurocost disability weights, a temporary cyclist injury had a mean disability weight of 0.0326. For those who sustained lifelong injuries, the mean years lived with disability (disability adjusted life years = DALYs) was 8.3 (211.251/25.45).

Table 3 shows cyclist injuries recorded in STRADA and presented by Nilsson et al. (2017). Nilsson et al. (2017) applied the WHO-GBD (GBD = Global Burden of Disease) disability weights to estimate the health impacts of the injuries. For temporary injuries, a mean disability weight of 0.0128 was found. For lifelong injuries, the mean disability weight was about 12.6.

Table 3 about here

Injuries recorded in STRADA are, on the average, slightly more serious than those recorded by the emergency centre in Oslo. The data presented by Nilsson et al. (2017) contain 5760 cyclists who sustained temporary injuries (98.6 % of the total), 77 cyclists who sustained lifelong injury (1.3 % of the total) and 2 killed cyclists (less than 0.1 % of the total). Applying the Eurocost disability weights, 98.8 % of injured cyclists recorded by the Oslo emergency centre sustained temporary injury and 1.2 % lifelong injury. If the WHO-GBD disability weights are applied, all injuries recorded by the Oslo emergency centre were classified as temporary. 70 percent of injured cyclists in Oslo sustained injuries with a disability weight of 0.05 or less. A very small minority (about 0.5 %) sustained injuries with a disability weight (per year) of 0.15 or more. This means that the median disability weight of injuries will be smaller than the mean disability weight.

4.2 Analytic choices in measuring health impacts of injuries

The following analytic choices arise:

1. The choice of source of data. An ideal source of data ought to have minimal underreporting and include the full range of injury severities.
2. Whether to use the Eurocost disability weights or the WHO-GBD disability weights when estimating the health impacts of injuries.
3. Whether typical health impacts are stated in terms of the mean values of the disability weights or the median values of the disability weights.

Table 4 compares the values of estimated disability weights between the two sources of data (Oslo emergency centre and STRADA), the two sets of disability weights (Eurocost and WHO-GBD) and the two measures of central tendency (mean and median).

Table 4 about here

It is seen that for temporary injuries, the mean disability weight is higher for STRADA than for the Oslo emergency centre. The median disability weight is considerably lower than the mean, and the differences between STRADA and the Oslo emergency centre are smaller than for the mean disability weights. For lifelong injuries, both mean and median disability weights for STRADA are substantially higher than for the Oslo emergency centre. When all injuries are considered, the mean disability weights are in the range between 0.13 and 0.24, with one exception. Median disability weights for all injuries are very diverse.

There were no fatal cyclist injuries in Oslo in 2014. Had there been one, involving 38.5 years of life lost, the mean disability weight for lifelong injuries would have increased from 8.3 to 9.4 years. The mean loss of health for all injuries (mean disability weight) would have increased from 0.1316 to 0.1497. This shows that mean values are very sensitive to the number of cases of lifelong or fatal injury.

The diversity of the results presented in Table 4, in particular for the median disability weights for all injuries means that the choice of statistic – mean or median – and the choice of disability weights – Eurocost or WHO-GBD – can make a big difference. The mean is pulled up by lifelong injuries. These injuries influence the median less. However, the mean is an unbiased estimator of the central tendency of a distribution and should be preferred. It is useful to know that it is greatly influenced by lifelong injuries, but that by itself is no good reason for rejecting it as an estimator of the typical loss of health associated with a cyclist injury.

Which of the two sets of disability weights should be preferred? Eurocost is more detailed than WHO-GBD. It contains a larger number of diagnoses. Furthermore, it assigns greater disability weights than WHO-GBD to most temporary injuries, but lower disability weights to lifelong injuries. Mean values estimated according to Eurocost are therefore less sensitive than WHO-GBD to the mix of temporary and lifelong injuries in a particular data set. These two characteristics suggest that Eurocost disability weights should be preferred. In the numerical examples given later in this paper, a mean disability weight of a cyclist injury of 0.15 has been used. This is slightly higher than the value of 0.13 estimated according to the data collected by the Oslo emergency centre, but reflects the fact that these data happen not to contain any fatal injuries, whereas the long-term expected number of fatal cyclist injuries in Oslo is greater than zero.

5 MODELLING THE PROBABILITY OF INJURY

As noted above, there is evidence that the risk of injury associated with cycling is not constant, but decreases as a function of distance cycled or the number of cyclists. There are two approaches to modelling this non-linearity of cyclist injury risk.

5.1 Cyclist risk per kilometre or trip

The first approach is to examine the relationship between distance cycled or frequency of cycling and risk of injury. Schepers (2012) studied whether more cycling reduced the risk of single-bicycle accidents. He found that this was the case. He applied a model of the form:

Number of cyclist injuries = $\alpha \cdot CYCL^{\beta_1} e^{(\sum_{n}^{i=1} \beta_n x_n)}$

Here CYCL represents kilometres cycled. An exponent β with a value less than one indicates that the number of injuries increases less than in proportion to the number of kilometres cycled. In the most precise model, Schepers found a value of 0.63 for the exponent.

Studies of Heesch et al. (2011), Marquéz and Hernández-Herrador (2017) and an ongoing study by Sundfør (2017) were also examined in order to assess the relationship between the amount of cycling and the number of injuries. Heesch et al. (2011) asked about cycling frequency. Their values (more than once per month, 1-2 times per week, 3-4 times per week and 5-7 times per week) were converted to a weekly frequency variable with values 0.5, 1.5, 3.5 and 6. The adjusted odds ratios for injury referring to these values (0.25, 0.60, 0.71 and 1.00) were used as dependent variable. A power function with an exponent of 0.53 was found to fit the relationship between cycling frequency and odds ratio for injury very well (R^2 = 0.9467).

Marquéz and Hernández-Herrador (2017) studied changes in the number of cycle trips and changes in the number of collisions between cyclists and cars in Seville, Spain, from 2000 to 2013. Reliable data on the number of trips were available for the years 2006-2013. Using these data, a power function was fitted with an exponent of 0.4485 (R^2 = 0.6494).

Sundfør (2017) collected self-reported data on distance cycled and injuries. Based on these data, the relationships shown in Figure 1 were found.

Figure 1 about here

Risk was found to decline as a function of distance cycled. For males, the risk elasticity shown in Figure 2 corresponds to an accident elasticity of 0.4. When data points were weighted in proportion to the number of accidents underlying each data point, the estimate of the accident elasticity was 0.382. For females, a power function fitting the data marginally worse than the exponential function shown in Figure 1 implied an accident elasticity of 0.37 (data points weighted). The five estimates of accident elasticity: 0.63 (Schepers), 0.53 (Heesch et al.), 0.4485 (Marquéz and Hernández-Herrador), 0.382 (Sundfør) and 0.37 (Sundfør) were combined by weighting them in inverse proportion to their sampling variance (standard error squared). The summary estimate of the accident elasticity was 0.5487. This means that when the amount of cycling increases from 1 to 10, the number of cyclist injuries is expected to increase from 1 to 3.518.

These models do not include the volume of motor vehicles, but are based data on distance cycled or the number cycle trips made only. The non-linearity of risk found in these models may reflect the fact that those who cycle longer or more often are more experienced and skilled than those who cycle shorter or more rarely. While these models are applicable when considering cycling only, they cannot be applied for assessing the effects of modal shifts, for example if car drivers change to cycling. One then needs to know how the risk of cyclist injury depends both on the number of cyclists and the number of cars. Studies of safety-in-numbers provide a basis for assessing how cyclist injury risk depends both on cycle volume and motor vehicle volume.

5.2 Safety-in-numbers for cyclists

Elvik and Bjørnskau (2017) have summarised evidence regarding safety-in-numbers by means of a meta-analysis of relevant studies. The models that were included in the meta-analysis were all of the following form:

Number of cyclist injuries $= e^{\beta_0} MV^{\beta_1} CYCL^{\beta_2} e^{(\sum_{n}^{i=1} \beta_n x_n)}$

Values of β_1 and β_2 less than one indicate a safety-in-numbers effect. Based on a random-effects meta-analysis, the summary estimates of coefficients were 0.432 for cycle volume and 0.499 for motor vehicle volume. These values have been applied to develop models of cyclist risk under alternative assumptions about modal shift. No change in trip length was assumed.

5.3 Alternative models of cyclist risk

To apply the results of the model of how cyclist risk depends on distance cycled, one needs to know the mean injury risk per kilometre cycled and the distribution of kilometres cycled in the population of cyclists. Probably the best current estimate of the mean injury risk for a cyclist in Norway is an estimate based on the data collected in Oslo in 2014 and travel behaviour data for the city. Bjørnskau and Ingebrigtsen (2015) estimate an injury risk of 8 per million kilometres cycled. This is a mean value for all cyclists in Oslo.

This mean value refers to the mean annual length cycled. An estimate of the mean length cycled each year by a cyclist in Oslo is not available, but the data collected by Sundfør (2017) show a mean annual distance (both genders combined) of 1199 kilometres. One cyclist stating an annual distance of more than 26,000 kilometres was omitted. The mean distance cycled by males was 1414 kilometres per year. 58 % cycled less than the mean distance, 42 % more. Among females, the mean annual distance cycled was 881 kilometres. 65 % cycled less than the mean distance, 35 % cycled more. Based on this, a numerical example has been developed for a mean annual distance cycled of 1200 kilometres, with 60 % cycling less than this and 40 % cycling more. A mean injury risk of 8 per million kilometres cycled has been assumed. A hypothetical population of 10,000 cyclists was divided into ten groups, each consisting of 1,000 cyclists. In each group, a mean annual cycling distance was specified. At the assumed injury rate, the 10,000 cyclists will sustain 96 injuries in total. The mean accident elasticity of 0.5487 estimated implies a risk elasticity of -0.4513. This was applied to estimate the risk for each group of cyclists, consistent with the restriction that mean risk was set at 8 injuries per million kilometres cycled.

Three models of cyclist risk based on safety-in-numbers have been developed:

1. A model in which the number of cyclists varies between 1000 and 10,000 in steps of 1000, while the number of motor vehicles is kept constant at 10,000.
2. A model in which the number of cyclists varies between 1000 and 10,000 in steps of 1000. At each step half of the increase in the number of cyclists comes from a reduction of the number of motor vehicles (e.g. when the number of cyclists increases from 1000 to 2000, the number of motor vehicles is reduced from 10,000 to 9,500).
3. A model in which the number of cyclists varies between 1000 and 10,000 in steps of 1000. At each step, all new cyclists are recruited from drivers of motor vehicles. At the initial step, there are 1000 cyclists and 10,000 motor vehicles. At the final step, there are 10,000 cyclists and 1000 motor vehicles.

There are thus four models: one based on the relationship between distance cycled and injury risk and three based on safety-in-numbers, assuming different degrees of modal shift associated with an increase in the number of cyclists. For each model, the expected number of cyclist injuries has been estimated. Table 5 shows the results.

Table 5 about here

The distance-based model shows the expected number of injuries among 1000 cyclists who annually cycle the distance stated in parentheses in column 1 of Table 5. Risk decreases as distance cycled increases. Those who cycle 450 km per year have an injury risk of 12.9 per million km cycled (5.8/450,000). Those who cycle 2300 km per year have an injury risk of 6.2 per million km cycled (14.2/2,300,000).

The safety-in-numbers-based models were calibrated so that at the initial step, the expected number of injuries was the same as for cyclists cycling the shortest annual distance. The numbers in columns 2-4 of Table 5 show, first, the number of cyclists and, second, the number of motor vehicles. When the number of cyclists increases without a corresponding reduction of the number of motor vehicles (model 2), the estimated number of injuries increases at almost the same rate as in the distance-based model. The increase, is, however, considerable less than proportional to the number of cyclists. An increase of the number of cyclists by a factor of 10 is associated with an increase in the expected number of injuries by a factor of 2.7 according to model 2.

The safety-in-numbers effect is reinforced if there is a modal shift. If half of the new cyclists are recruited among car drivers, the number of injuries increases by a factor of only 2. If all new cyclists are recruited among car drivers, a turning point is reached. Beyond the turning point, the number of injuries starts to drop and is lower when there are 10,000 cyclists than when there are 1000. However, when modal shifts are as large as in model 4, one may doubt whether the safety-in-numbers effect remains constant (i.e. whether the values of the regression coefficients are constant at all combinations of cycle and car volume). A recent study found evidence that the safety-in-numbers effect becomes weaker when the number of pedestrians or cyclists increases, but seems to be independent of the number of motor vehicles (Elvik 2017B).

Models based on safety-in-numbers are probably more widely applicable than models based on distance cycled or the number of cycle trips. Distance travelled is not considered in models of safety-in-numbers; these models typically rely on traffic counts made at specific locations. All one needs to apply a safety-in-numbers model is therefore a count of cyclists and motor vehicles at one or more locations in the area for which one wants to estimate how changes in cycling may influence the number of injuries. It is important to note, however, that short-term counts may be associated with considerable uncertainty (Kröyer 2015). Data on the number of injured cyclists in the area considered should, as discussed above, preferably be based on records kept by health professionals. Official accident statistics are very incomplete.

6 MONETARY VALUATION OF PREVENTING INJURIES

To include the health impacts of cycling, in particular cyclist injuries, in an economic assessment, it is necessary to assign a monetary value to the injuries. Nowadays, the most common way of assigning monetary values to life and limb is to rely on studies of the willingness to pay for the prevention of death or injury. In addition to the willingness-to-pay for preventing injuries, the costs should include medical treatment. The medical costs will, however, be small as most injuries are very slight. In this paper, the cost of cyclist injuries has therefore been estimated by relying on a valuation study made in Norway (Veisten, Flügel and Elvik 2010).

The current monetary valuation of a statistical life (i.e. a reduction in risk which statistically is equivalent to preventing one death) in Norway is about 35 million NOK, of which a little more than 31 million NOK refer to the human value of a life, i.e. to the pure welfare effect of preventing a fatality (Veisten 2016). The remainder of the value is mostly made up of lost output. This component will be disregarded in the following estimates, as virtually all cyclist injuries are so slight that they will not involve a loss of output which is anywhere close to the value of lost output when someone dies. This is supported by a recent study of self-reported injuries among pedestrians and cyclists, which found that 90 % were not absent from work as a result of the injury (Meltofte et al. 2017).

The Eurocost estimate, rounded as explained above, shows that a typical cyclist injury is associated with a health loss corresponding to 0.15 years lived with disability. The societal value of preventing such an injury is therefore 0.15 times the value of a life year.

Based on the data collected by the emergency medical centre in Oslo (Melhuus et al. 2015) the remaining life expectancy of an injured cyclist can be estimated to 47 years. If one assumes (NOU 2012:16) a real growth of income of 1.3 % per year and a discount rate of 4 % per year, the value of a life year can be estimated to 1,132,400 NOK. This value has the (welfare) value of a statistical life (31,255,000) as its present value. The societal cost of a cyclist injury is 0.15 · 1,132,400 = 169,900 NOK ≈ 170,000 NOK. The rate at which this cost is incurred depends on the injury rate per kilometre cycled. For mean injury risk, the expected injury cost per kilometre cycled is 8/1,000,000 · 170,000 = 1.36 NOK.

7 INCLUDING INJURY COSTS IN A HEALTH ECONOMIC ASSESSMENT

Most economic assessments of the health benefits and health costs of walking or cycling have relied on assumptions that are unique for each study (Mueller et al. 2015). One nevertheless finds many similarities between the studies. In particular, all studies find that the monetary value of the health benefits of active transport by far exceed the adverse health effects, which mostly consist of traffic injuries and exposure to air pollution.

The World Health Organization (WHO 2014) has developed a freely available online tool for economic assessment of walking or cycling and measures designed to promote these forms of travel. The tool estimates the effect on all-cause mortality of (increases in) walking or cycling. Changes in mortality are then converted to a monetary value by applying the value of a statistical life. Estimates of the effects on mortality of walking or cycling are based on a very comprehensive and rigorous meta-analysis (Kelly et al. 2014). The current version of the tool includes effects on mortality only. Traffic injuries are not included, nor are effects on morbidity of walking or cycling.

It may nevertheless be of some interest to assess whether the cost of cyclist injuries, as estimated in this paper, are in the same order of magnitude as the health benefits of cycling. The mean injury cost per kilometre cycled was estimated to be 1.36 NOK. To apply the WHO tool, the following parameter values were chosen:

Value of a statistical life (excluding lost output):	31,255,000 NOK
Net annual discount rate (adjusted for income growth):	2.6 %
Number of days per year cycled:	365
Number of years for which benefit was estimated:	10

The first two assumptions are consistent with those used when estimating injury cost per kilometre cycled. The third assumption was made for consistency and simplicity, as an annual cycling distance and annual injury rates were applied. The estimated benefit associated with reduced mortality was 45.57 NOK per kilometre cycled, which is considerably greater than the injury cost per kilometre cycled. The health benefit per kilometre cycled is constant, as the WHO tool treats it as a linear function of the number of METs (Metabolic Equivalent of Task; a measure of the intensity of physical activity in terms of calories consumed per hour, normalised by body size). Twice the distance cycled equals twice the number of METs, meaning that each kilometre produces the same number of METs.

8 DISCUSSION

There is an increasing interest in formal tools for assessing the impacts of physically active transport. Including non-fatal traffic injuries sustained by pedestrians or cyclists in health impact assessments is difficult, as these injuries are very incompletely recorded in official road accident statistics in all countries. To get realistic estimates of the number of injuries sustained while walking or cycling, one needs to set up dedicated data collection systems.

Injury recording systems at hospitals is one example of such a dedicated data collection system. A hospital-based data collection will not be complete; it will miss the slightest injuries. It will, however, be much more complete than police reported injury data. One may get a check on the completeness of hospital data by comparing them to self-reported injuries. Surveys (e.g. Heesch et al. 2011) have found that cyclists report injuries that did not get medical treatment. By comparing the number of injuries cyclists state were treated at a medical facility to the number of injuries recorded at that medical facility, one may at least get a rough check on completeness.

However, even if injuries are completely recorded, their relationship to the amount of cycling must be known to be able to include them in health impact assessments. Studies reviewed in this paper clearly indicate that the longer distance cyclists cover per year, or the more trips they take, the lower is the injury rate per kilometre or per trip. Studies of safety-in-numbers also indicate that injury risks are highly non-linear. This means that if cycling increases, it is unlikely that the number of cyclist injuries will increase in strict proportion to the amount of cycling.

Models developed indicate that the most influential factor with respect to how the number of injuries will change if there is more cycling, is whether an increase in cycling is associated with a modal shift from motor vehicles or not. A large modal shift was found to be associated with a smaller increase in the number of cyclist injuries than a small, or no, modal shift. It is, however, not clear whether the safety-in-numbers effect remains constant when there are large modal shifts.

This means that there is uncertainty associated with any estimate of how the number of cyclist injuries is likely to change if cycling increases. It is therefore sensible to perform sensitivity analyses. If, for example, the mean risk per million kilometres cycled in the ongoing study by Sundfør (2017) is used (62 injuries per million kilometres cycled) to estimate the cost of injuries, these costs could be as high as 10.54 NOK per kilometre cycled. Sundfør (2017) includes all self-reported injuries, many of which are very minor and were not treated by medical professionals. According to self-reports, only 28 percent of the injuries were treated by medical professionals. Yet, even a cost per kilometre of 10.54 NOK is much lower than the conservatively estimated benefit of 45.57 NOK per kilometre cycled.

9 CONCLUSIONS

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

1. Injury recording at emergency medical clinics and hospitals show that a considerably higher number of cyclists are injured than official road accident statistics suggest.
2. Most injuries sustained by cyclists are very slight and represent a health loss of less than 0.1 disability adjusted life years.

3. Cyclist injury risk declines as annual distance cycled increases. It also declines as the number of cyclists increases.
4. The societal costs of cyclist injuries are small when compared to the monetary value of the health benefits in terms of reduced all-cause mortality as estimated by means of the health economics assessment tool developed by the World Health Organization.

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REFERENCES

Amoros, E., Martin, J-L., Laumon, B. 2006. Under-reporting of road crash casualties in France. Accident Analysis and Prevention, 38, 627-635.

Bjørnskau, T., Ingebrigtsen, R. 2015. Alternative forståelser av risiko og eksponering. Rapport 1449. Oslo, Transportøkonomisk institutt.

Elvik, R. 2017A. Analyse av syklistskader i Oslo: rapporteringsgrad, helsekonsekvenser og sammenligning med svenske data. Arbeidsdokument SM 51134. Oslo, Transportøkonomisk institutt.

Elvik, R. 2017B. Exploring factors influencing the strength of the safety-in-numbers effect. Accident Analysis and Prevention, 100, 75-84.

Elvik, R., Bjørnskau, T. 2017. Safety-in-numbers: A systematic review and meta-analysis of evidence. Safety Science, 92, 274-282.

Elvik, R., Mysen, A. B. 1999. Incomplete accident reporting: a meta-analysis of studies made in thirteen countries. Transportation Research Record, 1665, 133-140.

Haagsma, J. A., Polinder, S., Lyons. R. A., Lund, J., Ditsuwan, V., Prinsloo, M., Veerman, J. L., Beeck, E. F. van. 2012. Improved and standardized method for assessing years lived with disability after injury. Bulletin of the World Health Organization, 90, 513-521.

Heesch, K. C., Garrard, J., Sahlqvist, S. 2011. Incidence, severity and correlates of bicycling injuries in a sample of cyclists in Queensland, Australia. Accident Analysis and Prevention, 43, 2085-2092.

Kelly, P., Kalhmeier, S., Götschi, T., Orsini, N., Richards, J., Roberts, N., Scarborough, P., Foster, C. 2014. Systematic review and meta-analysis of reduction in all-cause mortality from walking and cycling and shape of dose-response relationship. International Journal of Behavioral Nutrition and Physical Activity, 11:132 (online, 15 pp).

Kröyer. H. R. G. 2015. Accidents between pedestrians, bicyclists and motorised vehicles: Accident risk and injury severity. PhD dissertation. Lund University, Faculty of Engineering.

Maizlich, N., Linesch, N. J., Woodcock, J. 2017Health and greenhouse gas mitigation benefits of ambitious expansion of cycling, walking, and transit in California. Journal of Transport and Health (forthcoming).

Maizlich, N., Woodcock, J., Co, S., Ostro, B., Fanai, A., Fairley, D. 2013. He4alth cobenefits and transportation-related reductions in greenhouse gas emissions in the San Francisco bay area. American Journal of Public Health, 103, 703-709.

Marquéz, R., Hernández-Herrador, V. 2017. On the effects of networks of cycle-tracks on the risk of cycling. The case of Seville. Accident Analysis and Prevention, 102, 181-190.

Melhuus, K., Siverts, H., Enger, M., Schmidt, M. 2015. Smaken av asfalt. Sykkelskader i Oslo 2014. Oslo skadelegevakt. Oslo Universitetssykehus og Helsedirektoratet.

Meltofte, K., Andersen, C. S., Varhelyi, A., Schönebeck, S., Reumers, S., Hosta, P., Szagata, P. 2017. Estimated underreporting of traffic accidents based on self-reports. InDeV deliverable 5.2. Aalborg, Aalborg university.

Mueller, N., Rojas-Rueda, D., Cole-Hunter, T., Nazelle, A. de, Dons, E., Gerike, R., Götschi, T., Int Panis, L., Kahlmeier, S., Nieuwenhuijsen, M. 2015. Health impact assessment of active transportation: A systematic review. Preventive Medicine, 76, 103-114.

Nilsson, P., Stigson, H., Ohlin, M., Strandroth, J. 2017. Modelling the effect on injuries and fatalities when changing mode of transport from car to bicycle. Accident Analysis and Prevention, 100, 30-36.

Norges Offentlige Utredninger (NOU). 2012. Samfunnsøkonomiske analyser. NOU 2012:16. Oslo, Departementenes servicesenter.

Rabl, A., de Nazelle, A. 2012. Benefits of shifts from car to active transport. Transport Policy, 19, 121-131.

Rojas-Rueda, D., Nazelle, A. de, Andersen, Z. J., Braun-Fahrländer, C., Bruha, J., Bruhova-Foltynova, H., Desqeueyroux, H., Praznoczy, C., Ragetti, M. S., Tainio, M., Nieuwenhuijsen, M. J. 2016. Health impacts of active transportation in Europe. Plos One, 11(3): doi: 10.1371/journal.pone.0149990.

Rojas-Rueda, D., Nazelle, A. de, Teixiodo, O., Nieuwenhuijsen, M. J. 2013. Health impact assessment of increasing public transport and cycling use in Barcelona: A morbidity and burden of disease approach. Preventive Medicine, 57, 573-579.

Schepers, P. 2012. Does more cycling also reduce the risk of single-bicycle crashes? Injury Prevention, 18, 240-245.

Schepers, P., Fishman, E., Beelen, R., Heinen, E., Wijnen, W. 2015. The mortality impact of bicycle paths and lanes related to physical activity, air pollution exposure and road safety. Journal of Transport and Health, 2, 460-473.

Sundfør, H. B. 2017. Sykkelbruk – i trafikk og offroad. Eksponering og ulykker. Rapport under arbeid. Oslo, Transportøkonomisk institutt.

Tainio, M., Olkowicz, D., Teresinski, G., Nazelle, A. de, Nieuwenhuijsen, M. J. 2014. Severity of injuries in different modes of transport, expressed with disability-adjusted life years (DALYs). BMC Public Health, 14, 765 (http://www.biomedcentral.com/1471-2458/14/765.)

Veisten, K., Flügel, S., Elvik, R. 2010. Den norske verdsettingsstudien. Ulykker – verdien av statistiske liv og beregning av ulykkenes samfunnskostnader. Rapport 1053C. Oslo, Transportøkonomisk institutt.

Veisten, K. 2016. Et konkret forslag til en liten nedjustering av ex-ante verdsetting av "lettere skade" basert på Verdsettingsstudien. Arbeidsdokument av 21.9.2016. Oslo, Transportøkonomisk institutt.

Woodcock, J., Edwards, P., Tonne, C., Armstrong, B. G., Ashiru, O., Banister, D., Beevers, S., Chalabi, Z., Chowdhury, Z., Cohen, A., Franco, O. H., Haines, A., Hickman, R., Lindsay, G., Mittal, I., Mohan, D., Tiwari, G., Woodward, A. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. The Lancet, 374, 1930-1943.

Woodcock, J., Givoni, M., Morgan, A. S. 2013. Health impact modelling of active travel visions for England and Wales using an integrated transport and health impact modelling tool (ITHIM). Plos One, 8, e51462.

Woodcock, J., Tainio, M., Cheshire, J., O'Brien, O., Goodman, A. 2014. Health effects of the London bicycle sharing system: health impact modelling study. British Medical Journal, 348, g425 doi: 10.1136/bmj.g425.

World Health Organization(WHO). 2004. Global Burden of Disease 2004 update: disability weights for diseases and conditions. Geneva, World Health Organization.

World Health Organization (WHO). 2014. Health economic assessment tools (HEAT) for walking and cycling. Methods and user guide, 2014 update. Copenhagen, WHO regional office for Europe.

LIST OF FIGURES AND TABLES

Table 1:

Study	Scenario	Location(s)	Indicator of health impacts	Safety-in-numbers considered	Estimated impact on number of traffic injuries
Woodcock et al. 2009	Increased walking and cycling; reduced use of cars and motorcycles	London (England) and Delhi (India)	DALYs	No	Increase in London; decrease in Delhi
Rabl and de Nazelle 2012	Increased walking and cycling; cars use reduced correspondingly	Amsterdam and Paris for cyclist fatalities	Number of cyclist fatalities	No	Increase
Woodcock et al. 2013	Increased walking and cycling; reduced use of cars	Towns in England and Wales, except London	DALYs	Yes, as well as changes in speed of cars	Reduction assuming safety-in-numbers; increase otherwise
Maizlish et al. 2013	Increased walking and cycling; reduced use of cars	San Francisco Bay area	Fatalities, injuries and DALYs	Yes	Increase
Rojas-Rueda et al. 2013	Increased cycling and use of public transport; reduced use of cars	Barcelona	Number of injuries, DALYs	No	Reduction in most scenarios
Woodcock et al. 2014	Use of London bicycle sharing system	London	Number of injuries, DALYs	No	Increase
Schepers et al. 2015	Increased cycling associated with provision of bike lanes	Hypothetical Dutch city (100,000 inhabitants)	Life days gained per person	No, input was effect of bike lane	Reduction
Rojas-Rueda et al. 2016	Increased walking and cycling; reduced use of cars	Six European cities	Number of deaths; total and per inhabitant	Yes, in a sensitivity analysis	Increase in baseline analysis
Nilsson et al. 2017	Increased cycling; reduced use of cars	Stockholm	Number of fatalities and injuries, DALYs	No	Increase
Maizlish et al. 2017	Increased walking, cycling and use of public transport; reduced use of cars	California	Number of injuries, DALYs	Yes	Reduction in most scenarios

Table 2:

Injury	Number	Disability weight applied (EUROCOST)	Disability weight emergency room temporary	Probability of lifelong impairment	YLD for temporary	Disability weight emergency room lifelong	YLD for lifelong	Equivalent number of cases
Abrasions on head	88	Superficial injury (incl. contusions)	0.006	0.00	0.528			
Contusion of lower back, abdomen	41	Superficial injury (incl. contusions)	0.006	0.00	0.246			
Abrasions, shoulder, upper arm	105	Superficial injury (incl. contusions)	0.006	0.00	0.630			
Contusion of elbow	45	Superficial injury (incl. contusions)	0.006	0.00	0.270			
Contusion of fingers etc.	93	Superficial injury (incl. contusions)	0.006	0.00	0.558			
Contusion of hip or thigh	31	Superficial injury (incl. contusions)	0.006	0.00	0.186			
Contusion of knee	111	Superficial injury (incl. contusions)	0.006	0.00	0.666			
Contusion of ankle	47	Superficial injury (incl. contusions)	0.006	0.00	0.282			
Open wound on head	205	Open wound on head	0.013	0.00	2.665			
Open wound on back, abdomen	13	Open wound	0.013	0.00	0.169			
Open wound on elbow/lower arm	56	Open wound	0.013	0.00	0.728			
Open wound on wrist	40	Open wound	0.013	0.00	0.520			
Open wound on thigh	13	Open wound	0.013	0.00	0.169			
Open wound on lower leg	96	Open wound	0.013	0.00	1.248			
Open wound on foot	21	Open wound	0.013	0.00	0.273			
Fracture of foot/toes	19	Fracture of foot/toes	0.014	0.08	0.245	0.259	18.503	1.52
Concussion	111	Concussion	0.015	0.04	1.598	0.151	31.511	4.44
Fracture of hand/fingers	142	Fracture of hand/fingers	0.016	0.00	2.272			
Fracture of facial bones	41	Fracture of facial bones	0.018	0.00	0.738			
Dislocation/sprain of foot/ankle	37	Dislocation/sprain of foot/ankle	0.026	0.04	0.924	0.125	8.695	1.48
Dislocation/sprain of hand/fingers	126	Dislocation/sprain of hand/fingers	0.027	0.00	3.402			
Fracture of knee/lower leg	25	Fracture of knee/lower leg	0.049	0.23	0.943	0.275	74.319	5.75
Fracture of clavicula	90	Fracture of clavicula	0.066	0.02	5.821	0.121	10.237	1.80
Fracture of wrist	227	Fracture of wrist	0.069	0.00	15.663			
Fracture of rib	99	Fracture of rib	0.075	0.00	7.425			

Table 2, continued:

Injury	Number	Disability weight applied (EUROCOST)	Disability weight emergency room temporary	Probability of lifelong impairment	YLD for temporary	Disability weight emergency room lifelong	YLD for lifelong	Equivalent number of cases
Dislocation/sprain of shoulder/elbow	90	Dislocation/sprain of shoulder/elbow	0.084	0.00	7.560			
Dislocation/sprain of knee	35	Dislocation/sprain of knee	0.109	0.08	3.510	0.103	13.555	2.80
Fracture of upper arm	36	Fracture of upper arm	0.115	0.17	3.436	0.147	42.283	6.12
Fracture/sprain of vertebrae/spine	34	Fracture/sprain of vertebrae/spine	0.133	0.00	4.522			
Fracture of hip/pelvis	11	Fracture of hip	0.136	0.14	1.287	0.172	12.449	1.54
Total or mean	2128		0.0326	0.012	68.484		211.251	25.45

Table 3:

Injury	Number temporary	Number lifelong	Disability weight	Duration of disability (years)	Total weight	YLD temporary	YLD lifelong
Contusion or sprain (no further details)	643		0.064	0.038	0.0024	1.564	
Open wound (no further details)	1564		0.108	0.024	0.0026	4.054	
Fracture of foot/toes	94		0.077	0.073	0.0056	0.528	
Concussion	602		0.359	0.067	0.0241	14.480	
Fracture of hand/fingers	433		0.100	0.070	0.0070	3.031	
Fracture of facial bones	296		0.223	0.118	0.0263	7.789	
Dislocation/sprain of foot/ankle	16		0.074	0.019	0.0014	0.022	
Dislocation/sprain of hand/fingers	16		0.074	0.019	0.0014	0.022	
Fracture of knee/lower leg	170		0.271	0.090	0.0244	4.146	
Fracture of clavicula	376		0.143	0.112	0.0160	6.022	
Fracture of wrist	746		0.180	0.112	0.0202	15.039	
Fracture of rib	196		0.199	0.115	0.0229	4.485	
Dislocation/sprain of shoulder/elbow	132		0.074	0.034	0.0025	0.332	
Dislocation/sprain of knee	15		0.074	0.019	0.0014	0.021	
Fracture of upper arm	151		0.143	0.112	0.0160	2.418	
Fracture/sprain of vertebrae/spine	85		0.226	0.140	0.0316	2.689	
Fracture of hip/pelvis	44		0.247	0.126	0.0311	1.369	
Fracture of ankle	69		0.196	0.096	0.0188	1.298	
Fracture of femur	64		0.372	0.140	0.0521	3.333	
Fracture of skull/intracranial injury	22		0.431	0.107	0.0461	1.015	
Internal-organ injury	24		0.208	0.042	0.0087	0.210	
Eye injury	2		0.108	0.019	0.0021	0.004	
Fracture of femur		3	0.272	32.8	8.9216		26.765
Fracture of skull/intracranial injury		65	0.361	32.8	11.8408		769.652
Nerve injury		2	0.064	32.8	2.0992		4.198
Spinal-cord injury		7	0.725	32.8	23.7800		166.460
Total or mean	5760	77				73.874	967.075

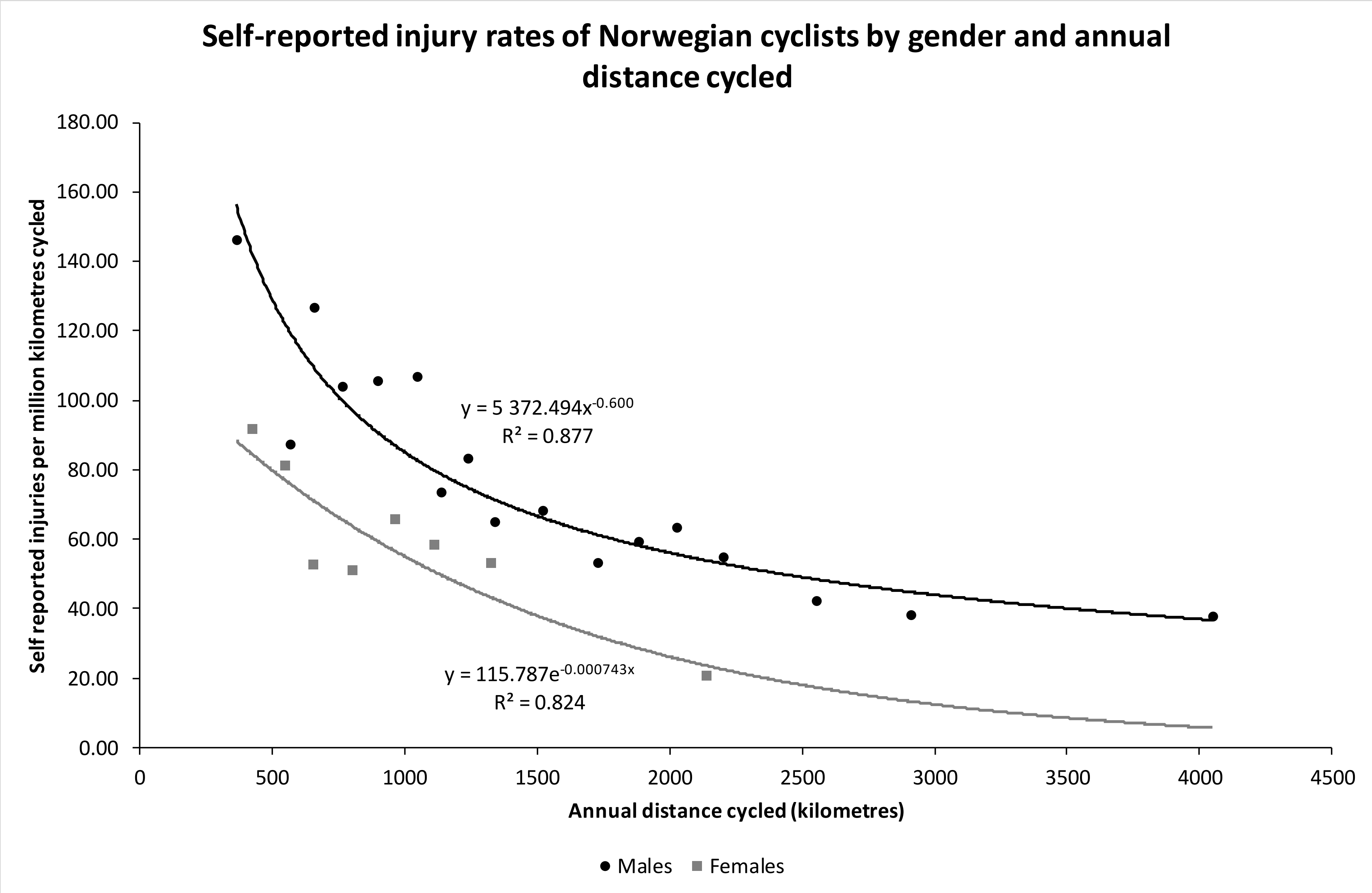
Table 4:

Study	Data source	Disability scoring	YLD (years lived with disability) per person: Temporary Mean	Temporary Median	Lifelong Mean	Lifelong Median	Total Mean	Total Median
Melhuus et al. 2015	Oslo legevakt	EUROCOST	0.0326	0.0144	8.31	6.13	0.1316	0.0787
		WHO-GBD	0.0087	0.0032	Empty cell	Empty cell	0.0087	0.0032
Nilsson et al. 2017	STRADA	EUROCOST	0.0371	0.0145	11.18	10.59	0.1840	0.1505
		WHO-GBD	0.0128	0.0032	12.56	11.84	0.1783	0.1554
Tainio et al. 2014	STRADA	WHO-GBD	0.0131	0.0070	12.80	11.50	0.2400	0.0087

Table 5:

Model 1: Distance cycled (km)	Model 2: No modal shift	Model 3: 50 % modal shift	Model 4: 100 % modal shift	Number of injuries (model 1)	Number of injuries (model 2)	Number of injuries (model 3)	Number of injuries (model 4)
1000 (450)	1000 – 10000	1000 – 10000	1000 –10000	5.8	5.8	5.8	5.8
1000 (600)	2000 – 10000	2000 – 9500	2000 – 9000	6.8	7.8	7.6	7.4
1000 (700)	3000 – 10000	3000 – 9000	3000 – 8000	7.4	9.3	8.8	8.3
1000 (800)	4000 – 10000	4000 – 8500	4000 – 7000	7.9	10.6	9.7	8.8
1000 (950)	5000 – 10000	5000 – 8000	5000 – 6000	8.7	11.6	10.4	9.0
1000 (1100)	6000 – 10000	6000 – 7500	6000 – 5000	9.4	12.6	10.9	8.9
1000 (1400)	7000 – 10000	7000 – 7000	7000 – 4000	10.8	13.4	11.2	8.5
1000 (1700)	8000 – 10000	8000 – 6500	8000 – 3000	12.0	14.2	11.5	7.8
1000 (2000)	9000 – 10000	9000 – 6000	9000 – 2000	13.1	15.0	11.6	6.7
1000 (2300)	10000 – 10000	10000 – 5500	10000 – 1000	14.2	15.7	11.6	5.0
10000 (1200)				96.0			

Figure 1:



Self-reported injury rates of Norwegian cyclists by gender and annual distance cycled
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Self reported injuries per million kilometres cycled
y = 5 372.494x^-0.600
R² = 0.877
y = 115.787e^-0.000743x
R² = 0.824
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Annual distance cycled (kilometres)
Males
Females