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Do The Health Benefits Of Cycling Outweigh The Risks?

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Abbreviations (alphabetical):

Abs, absorbance (10^{-5} m), a marker for (diesel) soot
BS, Black Smoke, a marker for (diesel) soot
BTEX, sum of benzene, toluene, ethylbenzene and xylene
CI, confidence interval.
EC, elemental carbon, equivalent to (diesel) soot
MET, Metabolic Equivalent of Task, a marker for energy expenditure
MI, myocardial infarction
$PM_{2.5}$, mass concentration of particles of less than 2.5 µm in size;
PM_{10}, mass concentration of particles of less than 10 µm in size;
RR, Risk ratio
TSP, total suspended dust
UFP, ultrafine particle count

Outline of section headers:

ABSTRACT

Objective

Although from a societal point of view a modal shift from car to bicycle may have beneficial health effects due to decreased air pollution emissions, decreased greenhouse gas emissions and increased levels of physical activity, for the shifting individual adverse health effects such as higher exposure to air pollution and risk of a traffic accident may prevail. This paper describes whether the health benefits from the increased physical activity of a modal shift for urban commutes outweigh the health risks.

Data sources and extraction

We have summarized the literature for air pollution, traffic accidents and physical activity using systematic reviews supplemented with recent key studies.

Data synthesis

We quantified the impact on all-cause mortality when 500,000 people would make a transition from car to bicycle for short trips on a daily basis in the Netherlands. We have expressed mortality impacts in life years gained or lost making use of life table calculations.

For the individuals who shift from car to bicycle, we estimated that beneficial effects of increased physical activity are substantially larger (3 – 14 months gained) than the potential mortality effect of increased inhaled air pollution doses (0.8 – 40 days lost) and the increase in traffic accidents (5 – 9 days lost). Societal benefits are even larger due to a modest reduction in air pollution and greenhouse gas emissions and traffic accidents.

Conclusions

On average, the estimated health benefits of cycling were substantially larger than the risks relative to car driving for individuals shifting mode of transport.

INTRODUCTION

Recently, policy interest in promoting cycling as a mode of transport has increased substantially within Europe. Several capitals, such as Copenhagen (1995), Helsinki (2000), Oslo (2002), Stockholm (2006), Barcelona (2007), Paris (2007) and Brussels (2009) have implemented low-cost rental systems aimed at stimulating commuters to use bicycles for the typically short urban trips. Motive for these policies is more often the reduction of traffic congestion than promotion of health. In 2005, the EU has formulated an important area of action: 'addressing the obesogenic environment to stimulate physical activity' (Commission of the European Communities 2005). Attitudes and policies towards active commuting have recently been discussed (Lorenc et al. 2008; Ogilvie et al. 2004). The PEP project provides guidance to policy-makers and local professionals how to stimulate cycling and walking (www.healthytransport.com). The promotion of walking and cycling is a promising way to increase physical activity across the population by integrating it into daily life. Promoting cycling for health reasons implies that the health benefits of cycling should outweigh the risks of cycling. Though society may benefit from a shift from private car use to bicycle use (e.g. because of reduced air pollution emission), for the shifting individual disadvantages may occur. While the individual may benefit from increased physical activity, at the same time he/she inhales more pollutants due to an increased breathing rate. The risks of getting involved in traffic accidents may increase as well as the severity of an accident. A study in Vancouver (Marshall et al. 2009) illustrated that especially in the city centre high walkability neighbourhoods had high traffic density leading to high air pollution concentrations for a traffic-related primary pollutant but not for a secondary pollutant (ozone). For cycling, similar issues may occur.

The aim of this paper is to assess quantitatively whether the health benefits of the use of a bicycle instead of a private car for short trips outweigh the health risks. The risks and benefits will be evaluated both for the individuals who shift from car driving to cycling and for society as a whole.

METHODS

We focus on the comparison of private car driving versus cycling because most trips are made by car and the use of the private car is related to many negative aspects, including congestion, use of physical space, reduction of outdoor activities, air pollution and noise. In the Netherlands, 20 and 30% of total car trips (15.9 million trips/day) are respectively for shopping and commuting purposes (MON 2007, Beckx et al. 2009a,b). Approximately 50% of all car trips are shorter than 7.5 km, which is short enough to make travel by bicycle a feasible alternative.

In the quantitative comparison between car driving and cycling we considered air pollution, traffic accidents and physical activity as main exposures. We have summarized the relevant evidence of health effects related to air pollution, traffic accidents and physical activity separately. For these sections, we made use of published (systematic) reviews, supplemented with more recent key studies.

Health effects related to air pollution, traffic accidents and physical activity differ, e.g., with traffic accidents resulting in injuries and physical activity affecting cardiovascular disease. Therefore, we compare potential effects of these exposures (in conjunction with driving or cycling) on *mortality* rather than morbidity. In addition, epidemiological evidence of associations of these exposures with mortality is stronger than associations with other outcomes, particularly for physical activity; all three exposures have been associated with mortality, so that a common metric can be used to quantify their potential effects; and mortality is reported more consistently than other health outcomes. In particular, minor injuries associated with traffic accidents are much more likely to be underreported than deaths due to traffic accidents.

For deriving the relative risks comparing car driving and cycling, we specified a hypothetical scenario based upon statistics in the Netherlands. The scenario assumes a transition from car driving to cycling for 500,000 people aged 18 to 64 yr for short trips on a daily basis in the Netherlands. We made calculations for a daily travelled distance of 7.5 km and 15 km, e.g. people commuting to and from work for 3.75 km (the average short trip) or 7.5 km (the maximum short trip). Our scenario implies a shift of about 12.5% of the 7.95 million short car trips, an ambitious yet not unrealistic percentage. In the Netherlands, 40.8% of the persons older than 18 years own both a car and a bicycle and therefore may be able to shift modes on a daily basis. In this paper, we will focus on the Dutch situation because of data-availability, but in the overall discussion we will illustrate that the use of this Dutch scenario has not substantially affected our conclusions. The scenario is mostly used to calculate travel time and kilometres driven, inputs needed to calculate air pollution, physical activity and accident impacts, combined with more generic concentration response functions.

We have expressed mortality impacts in life years gained or lost estimated with life table calculations (Miller and Hurley 2003). For the calculation we used a population of 500,000 people aged 18 to 64, distributed in age categories comparable to the 2008 Dutch population (CBS 2008). We have estimated the effects on this population for a lifetime.

AIR POLLUTION EXPOSURES AND HEALTH EFFECTS

Air pollution exposure during cycling and car driving

Since the 1990's various studies have measured air pollution exposure levels associated with different modes of transport (Kaur et al. 2007). In recent studies, the emphasis has been on fine and ultrafine particles (particles with aerodynamic diameter ≤2.5μm and 0.1 μm respectively), because these are the main pollutants related to human health effects. Driving or cycling in traffic may result in air pollution exposures that are substantially higher than overall urban background concentrations (Kaur et al. 2007). Consequently, even relatively short times spent in traffic may contribute significantly to daily exposures (Van Roosbroeck et al. 2007; Beck et al 2009a,b; Fruin et al. 2004; Marshall et al, 2006). Studies that specifically compared exposures during car driving and cycling within the same study are summarized in Table 1.

Overall, air pollution *exposures* experienced by car drivers were modestly higher than those experienced by cyclists, with mean ratios of 1.16 for $PM_{2.5}$, 1.01 for ultrafine particles and 1.65 for elemental carbon or soot. However, increased physical activity results in higher minute ventilation in cyclists than car drivers, with estimates from two Dutch studies reporting that the minute ventilation of cyclists was 2.3 times (van Wijnen et al. 1995) and 2.1 times (Zuurbier et al. 2009) higher than that of car drivers. Therefore, *inhaled doses* of fine particles and to a lesser extent elemental carbon may be higher in cyclists. The difference in exposure between cyclists and car drivers depends on a large number of factors such as selected route, car speed, trip duration, car type, ventilation status, driving behaviour, street configuration and weather conditions (Kaur et al. 2007). Trip duration might also be higher for cyclists, though this may be highly dependent on the setting. For example, in a study conducted in 11 Dutch cities there was no difference in the time required to bicycle versus drive short distances (Boogaard et al. 2009), but for longer trips cars were faster than cyclists (Zuurbier et al. 2010).

Health effects of in traffic exposures

The short exposures typical for commuting have not been studied extensively in air pollution epidemiology, in contrast to 24-hour average exposures or long-term (annual average) exposures (WHO 2006). Several studies have documented that long-term exposure to traffic-related air pollution is associated with adverse health effects including increased mortality (WHO 2006).

The few epidemiological studies of in traffic air pollution exposures are summarized in Table 2, suggesting that these exposures result in physiological changes (including airways and systemic inflammation, lung function decrements) in healthy adults and asthmatics and possibly more severe adverse effects (myocardial infarction).

Furthermore, there is a fairly substantial body of evidence of human controlled exposure studies in which volunteers have been exposed for 1 to 2 hours to diesel exhaust and for comparison filtered air (Supplement Material, Table 1). Typically the evaluated exposures (100 – 300 $\mu g/m^3$) are higher than encountered in ambient air, though not excessively. Because of ethical concerns, only physiological effects have been studied with this study design. These studies have documented airway and systemic inflammation following exposure to diesel exhaust in patients and in healthy subjects.

Assessment of the modal shift impact on air pollution exposure related mortality

Individual effects

Since the physiological changes observed in epidemiological and controlled exposure studies likely play a role in the pathway to cardiac events of long-term exposure, it is plausible that these more adverse effects may occur in susceptible subjects. We calculated the potential impact on mortality of a transition from using a car to a bicycle for a half hour (7.5 km) or one hour (15 km) commute based upon relative risk estimates from long-term exposure studies of mortality in association with $PM_{2.5}$ (Pope et al. 2002) and Black Smoke (Beelen et al. 2008).

The derivation of these risk estimates is provided in Supplement Material Tables 2a and 2b, results are shown in Table 3. We assumed that the actual risk related to long-term air pollution exposure is determined by the inhaled daily dose of fine particles. First, we calculated the inhaled pollution dose during commuting (car driving or cycling) and non-commuting hours based on prior information concerning minute ventilation rates (in L/min) and $PM_{2.5}$ and BS exposures (in $\mu g/m^3$) during sleep, rest, driving or cycling. Next, we estimated the total daily dose for $PM_{2.5}$ and BS (in μg/day) for driving or cycling. We then used the ratio of the total daily doses for the two travel modes to derive an 'equivalent' change in $PM_{2.5}$ or BS concentration (in $\mu g/m^3$), that could be normalized to the $10\mu g/m^3$ increase in long-term exposures used by Pope et al. (2002) and Beelen et al. (2008) to estimate the relative risk associated with the estimated change in long-term $PM_{2.5}$ and BS exposures that would result from a shift to commuting by bicycle instead of by car

Assuming equal toxicity of particles, the estimated relative risk associated with the change in fine particle inhalation due to cycling instead of car driving ranges from 1.005 to 1.010. If we assume that traffic particles are more toxic than ambient $PM_{2.5}$ in general, these RR estimates range from 1.026 to 1.053. This assumption is supported by an analysis of particles from different sources, indicating the strongest associations with mortality from traffic particles (Laden et al. 2000). If the assessment is based upon Black Smoke, RR estimates are smaller (between 1.001 and 1.012).

Societal effects

The modal shift will reduce overall air pollution levels which may result in health benefits of the general city population. An indication of the potential reduction in air pollution was obtained by using the Dutch CAR-model (Eerens et al. 1993). For a typical major urban street with a traffic intensity of 10,000 vehicles per day, for a 12.5% reduction in traffic intensity, concentration reductions were 1.3 $\mu g/m^3$ for NO_2 and 0.4 $\mu g/m^3$ for PM_{10}. The relative risk of long-term exposure to NO_2 expressed per 10 $\mu g/m^3$ on all-cause mortality is 1.10 (Tonne et al. 2008). This implies that for the approximately 800,000 -1,600,000 subjects living in major streets in the Netherlands, mortality rates could be 1.012 times lower. This relative risk is of the same order of magnitude as the estimated increased risk to the cyclist described in the previous section and applies to a larger population.

ACCIDENTS

According to the World Health Organization (WHO), road traffic injuries accounted for approximately 2% of all global deaths, making them the eleventh leading cause of global deaths (WHO 2004). The rates of road traffic death vary considerably between countries, transport mode, type of area (urban or rural) and person. Amongst several European countries the highest fatality rates are about 3.5 times higher than the lowest figures (Supplement Material, Figure 1, http://www.internationaltransportforum.org.).

How safe is cycling compared to car driving for an individual?

Table 4 shows the estimated numbers of traffic deaths per age category per billion passenger kilometres travelled by bicycle and by car (driver and passenger) in the Netherlands for 2008 (CBS, 2008). These data suggest that there are about 5.5 times more traffic deaths per km travelled by bicycle than by car for all ages, and that cycling is riskier than travel by car for all age groups except young adults (age 15-30y), with about 9 times more deaths among those <15y of age, and 17 times more deaths among those >80y. The comparison in Table 4 probably overestimates the difference between cyclists and car drivers for short trips, because the relatively safe long car trips driven on highways are included. Across Europe, 8% of traffic deaths occur on the motorways, whereas 25% of the kilometres driven are on motorways (European Road Transport Safety, 2008). Risks for non-fatal accidents are higher for cyclists than for car drivers as well (Supplement Material, Table 3).

How safe is cycling compared to car driving for the society?

For society, also the risk that car drivers present to cyclists and pedestrians has to be taken into account. For the Netherlands, an analysis has been made to compare the risks of a fatal accident for car drivers and cyclists, including the risk to other road users (European Commission, 1999). The analysis excluded motorways, as cyclists cannot use these roads. Mortality rates were similar for car drivers and cyclists (20.8 versus 21.0 deaths per million km travelled). People above 50 get less frequently involved in fatal accidents when driving a car than when driving a bicycle, but the opposite is true for people in the age 18 – 49 (Supplement Material, Table 4). Jacobsen (2003) showed that in different European countries traffic deaths of cyclists is inversely related to the amount of cycling (Supplement Material, Figure 2) suggesting a safety in numbers effect.

Assessment of the modal shift impact on traffic accidents related mortality.

For 18 – 64 yr old individuals, the risk of a fatal accident while cycling is about 4.3 times higher compared to the same distance by car (Table 4). The fatal traffic accident rate for cyclists aged 20-70y is about 8.2 deaths per billion passenger km travelled, whereas the risk for car drivers and passengers the rate is 1.9 deaths per billion passenger km travelled (Table 4). A population of 500,000 commuting 7.5km per day will commute 1.36785 billion km/year (7.5km/day*365 days/y*500,000). Based on the data shown in Table 4, we estimate that this amount of car travel would result in approximately 2.6 deaths per year (1.9*1.36785). An equivalent amount of bicycle travel would result in approximately 11.2 deaths per year (8.2*1.36785). In the Netherlands, the all-cause mortality rate for 18-64 year old persons is 235.1 per 100,000 per year (CBS 2008) or 1,176 persons per 500,000 per year. Hence, among 18-64 year olds, the relative risk of all-cause mortality associated with a 7.5km/day shift from driving to cycling would be (1,176 + (11.2-32.6)) /1,176=1.007. When we use age-specific data, relative risks ranged from 0.996 to 1.010. For the 15 km scenario, age specific relative risks ranged from 0.993 to 1.020.

The <u>societal</u> impact of a modal switch on the number of fatal accidents largely depends on which people switch from car to bicycle. If it is the average population, the impact (including risk presented to other road users) would be practically zero (Supplement Material, Table 4), but if young car drivers would switch to the bicycle, it would decrease the number of fatal accidents. The opposite is true for the elderly car drivers.

PHYSICAL ACTIVITY

Levels of inactivity are high in virtually all developed and developing countries. The WHO estimates that 60% to 80% of the world's population does not meet the recommendations required to induce health benefits (WHO 2007a). For Europe 62.4 % inactive adults are estimated ranging from 43.3 % (Sweden) to 87.7% (Portugal) (Varo et al. 2003). In the Netherlands about 62% of the population is sedentary (Varo et al. 2003). WHO estimates that the prevalence of physical inactivity accounts for 22% of cardiovascular disease prevalence globally (WHO 2007a). There is sufficient evidence for an association between physical activity and mortality, cardiovascular disease (hypertension), diabetes, obesity, cancer (colon and breast), osteoporosis and depression (Bauman 2004; Warburton et al. 2006). Since only few studies specifically reported on the beneficial health effects of cycling we also summarized the quantitative evidence of beneficial health effects of physical activity, making use of review papers.

Cycling and physical activity recommendation

Recently, the American College of Sports Medicine and the American Heart Association published an updated recommendation for physical activity (Haskell et al. 2007). To promote and maintain health, all healthy adults aged 18 – 65 yr need moderate-intensity aerobic physical activity for a minimum of 30 minutes on five days each week or vigorous-intensity aerobic activity for a minimum of 20 minutes on three days each week. Also, combinations of moderate- and vigorous intensity activity can be performed to meet this recommendation. For young people 60 minutes of moderate to vigorous physical activity on a daily basis is recommended (Strong et al. 2005). In several physical activity studies metabolic equivalent (MET) is used as an indicator of physical activity and the minimum goal should be in the range of 500 to1000 $MET{\cdot}min{\cdot}week^{-1}$. Leisure cycling or cycling to work (speed 15 $km{\cdot}hr^{-1}$) has a MET value of 4 and is characterized as a moderate activity (Ainsworth et al. 2000). Hence, a person shifting from car to bike for a daily short distance of 7.5 km would meet the minimum recommendation (7.5 km / 15 $km{\cdot}hr^{-1}$ = 30 minutes) for physical activity in 5 days (4 MET x 30 minutes x 5 days = 600 $MET{\cdot}min{\cdot}week^{-1}$).

Health effects and assessment of the modal shift impact on mortality

Table 5 provides the summary estimates from reviews for the impact of physical activity on all-cause mortality. The table only includes estimates that are relevant to compare the risks for cyclists and car drivers. It is difficult to synthesize information across studies because investigators have measured physical activity in different ways and classified physical activity according to different dose schemes that often are difficult to compare directly (Lee and Skerrett 2001). Several reviews have assessed that the relative risk of mortality for those who meet the recommended levels of physical activity compared to the inactive group is between 0.65 and 0.80 (Bauman 2004; Lee and Skerrett 2001; Warburton et al. 2006).

Three studies have directly assessed mortality related to cycling to work. In a prospective study in Copenhagen, the relative risk of the group bicycling to work was 0.72 (95% CI, 0.57-0.91) compared to other modes of transport after multivariate adjustment, including leisure time physical activity (Andersen et al. 2000). The relative risk for physically active groups compared with the sedentary group decreased with activity level: 0.68, 0.61 and 0.53 (Andersen et al. 2000). In the Shanghai Women's Health study exercise and cycling for transportation were both inversely and independently associated with all-cause mortality (Matthews et al. 2007). Hazard ratios for the group cycling 0.1-3.4 metabolic equivalent hours per day were 0.79 (95% CI, 0.61-1.01) and for the group cycling more than 3.4 metabolic equivalent hours per day 0.66 (95% CI, 0.40-1.07) compared to the non cycling group. A Finnish study that combined cycling and walking to work versus non-active commuting also showed significantly lower relative risks for active commuters in the range of 0.71 and 0.79 (Hu et al. 2004). According to the reviews and the three cycling studies the relative risk for all cause mortality is in the range of 0.50 to 0.90 (Table 5).

An expert panel determined a generally linear relationship between physical activity level and the rates of all-cause mortality, total CVD and coronary heart disease incidence and mortality (Kesaniemi et al. 2001). There is thus evidence that health gains occur for physically active and non-active persons, though the magnitude of these benefits may differ.

To calculate the potential impact of the modal shift on mortality, we directly used the range of RR estimates (0.50 - 0.90) presented in table 5.

COMPARISON OF LIFE YEARS GAINED OR LOST

For the people who shift from car to bicycle use for short trips, we estimated that the beneficial effect on all-cause mortality rates of the increased physical activity due to cycling is substantially larger (relative risk of 0.50 – 0.90) than the potential mortality effect of increased inhaled air pollution doses (relative risks of 1.001 – 1.053) and the effect on traffic accidents (age specific relative risks of 0.993 – 1.020). The estimated gain in life expectancy per person from an increase in physical activity ranged from 3 to 14 months (Table 6). The estimated life expectancy lost due to air pollution (0.8 – 40 days) and traffic accidents (5 – 9 days) were much smaller. On average the benefits of cycling were about 9 times larger than the risks of cycling, compared to car driving for the individuals making the shift, calculated as 337,896 / (28,135 + 9,639). The estimated number of life years gained still exceeded the losses when the lowest estimate for physical activity was compared with the highest estimate for air pollution and traffic accidents (benefits / risks ratio of 2).

The largest estimated gain in life years was for the elderly (Supplement Material, Table 6). The ratio of life years gained to lost was 8.4 for the <40 yr, 8.6 for the 40-64 yr and 10.8 for the 65+ yr groups.

The relative benefits of a 7.5 versus 15 kilometre distance are probably similar. A 15 km distance (1-hour commute) increases the life years lost for air pollution from 20 to 40 days based on $PM_{2.5}$ and increases the life years lost for traffic accidents from 5 to 9 days. The total estimated days lost per person is thus 49 for a 15 km distance and 25 for a 7.5 km distance. The relative risk of physical activity is increased but difficult to quantify, with the approach employed here. Using the data from Matthews et al., for the 7.5 km distance, the relative risk would be 0.79 and 0.66 for the 15 km distance, assuming 4 MET associated with cycling. These relative risks translate in 280 and 173 days gained.

OVERALL DISCUSSION

Principal findings

We quantitatively compared the health benefits from physical activity with the risks related to air pollution and traffic accidents between cycling and car driving for short trips, distinguishing the (shifting) individuals and society as a whole. Estimated inhaled air pollution doses were higher in cyclists. The risk of a fatal traffic accident is higher for cyclists than for car drivers. Substantial benefits of physical activity have been demonstrated, including decreased cardiovascular disease and mortality.

For the people who shift from car to bicycle, we estimated that the well-documented beneficial effect of increased physical activity due to cycling resulted in about 9 times more gains in life years than the losses in life years due to increased inhaled air pollution doses and traffic accidents. For the society as a whole this can be even larger, because of reduced air pollution emissions. If the risk presented to other road users is included, the risk of a fatal traffic accident is virtually the same for cyclists and car drivers.

Strengths and weaknesses

The strength of our assessment is especially the quantitative comparison of benefits and risks, in a common scenario for the three stressors evaluated. It could be argued that the Copenhagen (Andersen et al. 2000) and Chinese studies (Matthews et al. 2007) of the effects of bicycling on mortality already demonstrated the *net* effect of physical activity on all-cause mortality, including the negative effects on fatal traffic accidents and air pollution. However, the size of the potential negative health effects was not quantified separately in those studies. Therefore it is difficult to transfer the net effect of these studies to other locations, where traffic accident rates and air pollution may be different. Because in our assessment, the separate risks have been disentangled it is possible to make assessments for different settings, by using other input data for e.g. traffic mortality rates.

We performed our calculations for the Netherlands. Here an extensive cycling infrastructure exists and priority is given to cyclists over other traffic, factors that contribute to regular cycling. Restriction to car use through traffic calming in residential areas and car-free zones influence cycling behaviour as well (Pucher and Dijkstra 2003). Apart from the highest average distance cycled per person, the Netherlands is also one of the safest countries for fatal traffic accidents. In countries like the UK, Spain and France the risk of a fatal traffic accident of cyclists is substantially higher, probably also relative to car driving (Supplement Material, Figure 2). When we repeated the traffic accident calculations for the UK, where the risk of dying per 100 million km for a cyclist is about 2.5 times higher (Supplement Material, Figure 2) and assuming the same fatality risk for car drivers as in the Netherlands, resulting life expectancy losses were approximately 14 days per person, based on 2005 population data from the UK and Wales. Overall benefits of cycling are still 7 times larger than the risks.

Calculations on mortality impacts were performed for people aged 18 to 64 yr, as those people are more likely to make the modal shift. Age specific analysis showed that the relative benefits of cycling are highest in the older age categories. This may be even more pronounced if we had taken into account that the relative risks of physical activity may be larger for the elderly (Vogel et al. 2009). The empirical evidence for higher relative risks in elderly related to long-term exposure to air pollution is weak, e.g. in the large ACS study there were no differences in relative risk for $PM_{2.5}$ (Pope et al. 2002). We did not include children in our assessment since they are unable to drive a car and therefore a modal shift is not possible. Because of our focus on mortality effects (being extremely rare in children), we could not quantitatively compare risks for children as car passengers or as cyclists for physical activity and air pollution. The benefits of physical activity in children are however considered important, both for current and future health.

Overall relative risks may largely reflect the response from sensitive subgroups. For all stressors, the elderly are likely more susceptible and we documented in an additional analysis that the ratio of benefits and risks was highest for the 65+ year olds. For air pollution, subjects with pre-existing cardio-respiratory disease and for physical activity sedentary people may be more susceptible, subgroups that may partly overlap. Hence both the risks and benefits may be higher than in the population average analysis.

In summary, it is unlikely that the conclusion of substantially larger benefits from cycling than risks is strongly affected by the assumptions made in the scenario, including the use of data from the Netherlands. Since concentration-response functions are mostly based upon studies in Europe and North America, they may not apply in developing countries. For air pollution, there are no studies on long-term mortality effects in developing countries. The generally higher ambient air pollution concentrations could lead to higher losses in life years comparing cycling and car driving. Traffic accident statistics for the Netherlands are probably not transferable to developing countries. For physical activity there is evidence from a Chinese study, with very similar benefits. Hence very large differences in concentration-response functions for air pollution and traffic accidents from the functions we used would be necessary to tip the balance between benefits and risks.

For *air pollution*, there is considerable evidence that long-term and short-term exposure, is related to increased cardio-pulmonary mortality (Brunekreef and Holgate 2002). There are no studies of mortality effects specifically related to in traffic exposures. We estimated the effect of shifting mode using two major long term mortality cohort studies (Beelen et al. 2008; Pope et al. 2002), making assumptions about the contribution of traffic participation to the total inhaled dose of fine particles and (diesel) soot. Relative risks comparing cycling and car driving were small for both approaches, with the lower estimates based upon Black Smoke probably most realistic, as this component is more specific for traffic emissions.
The actual risk may be smaller because cyclists could more easily choose a low traffic route. The substantial influence of *route* has been documented in various monitoring and modelling studies (Adams et al. 2001; Hertel et al. 2008; Kingham et al. 1998; Strak et al. 2010). A study in Utrecht found 59% higher ultrafine particle exposure for cyclists along a high traffic route compared to a low traffic route (Strak et al. 2010). Walking close to the kerb in London greatly increased personal exposures (Kaur et al. 2005). For cyclists position on the road is likely important as well, as it determines distance to motorized traffic emissions. Urban planning may also contribute by separating cycle lanes from heavily trafficked roads (Thai et al. 2008).

For *society*, reduced overall air pollution levels may result in lower mortality from long-term exposure of city dwellers. The potential benefits we estimated based on NO_2 reductions were in the same order of magnitude as the potential risks for the individuals shifting.

Table 4 shows that the modal shift will lead to an increase in *traffic accident deaths*. The risk ratio may be lower than we used by the 'safety in numbers effect' (Supplement Material, Figure 2). Car-drivers may take more account of cyclists, resulting in fewer accidents per car-kilometre, when cyclists form a bigger part of the traffic (Jacobsen 2003). Traffic fatality and injury rates in Germany and the Netherlands (with relatively high levels of cycling and walking) were relatively low compared to those of the United States (Pucher and Dijkstra 2003). However, whether this reduction is due to a 'safety-in-numbers' effect or a result of more biking lanes cannot easily be disentangled. The WHO concluded that if promotion of active commuting is accompanied by suitable transport planning and safety measures active commuters are likely to benefit from the 'safety-in-numbers' effect (WHO 2007b). The risk ratios could also be higher because the less experienced cyclists making the shift could be more vulnerable to an accident. We cannot quantify this effect.

Even when origin and destination is the same, cars and bicycles often take different routes (Witlox 2007). The same short trip for a car may be 20 – 50 % longer than for a bicycle. Our calculations are based on comparisons per kilometre. If we would make a trip-based comparison, thus a lower risk ratio of a fatal accident for cyclist compared to car drivers would be found,. Furthermore, we did not take into account the concept of constant travel time budgets (van Wee 2006): a change of travel time will be compensated by a change of destination. When taking the bicycle, the shop next door is preferred over the shop with a greater choice further away. These factors would lead to lower risk ratios than we used.

Relative risks for different *physical activity* definitions (total physical activity, meeting the physical activity guideline, active commuting) were quite consistent. An important issue is whether the comparison between subjects with lower and higher physical activity can be used to assess the health effects of a *change in physical activity* related to a shift towards active commuting. Baumann (2004) showed that persons who were already in the highest quartile of fitness at baseline had a significantly lower mortality when they became even more active. In another study, people who went from unfit to fit over a 5-year period had 44% relative risk reduction compared with people who remained unfit (Blair et al. 1995). The largest improvements in health status are seen in inactive persons who change their lifestyle and become physical active (Warburton et al. 2006). A review by Erikssen (1998) suggested similar health benefits from an increase in physical activity for active and sedentary persons. Already active persons could have lower benefits of the extra physical activity, leading to relative risks up to 0.90. If only active persons would shift, lower overall benefits of cycling compared to car driving will be found (ratio of life years gained to lost of 4 instead of 9).

An increase in cycling does not necessarily lead to an increase in total physical activity, if it is associated with reduced activity in another domain (Thomson et al. 2008; Forsyth et al. 2008). The empirical evidence for substitution is weak and increased fitness could also lead to more physical activity in leisure time. If we assume that for 25% of the population no health gains occur because of substitution, the ratio of benefits to risks (central estimates from Table 6) would be reduced from 8.9 to 6.7. Only if for 89% of the population no increase in total physical activity occurs due to substitution, benefits and risk become equal.

We have not considered the negative effects of physical activity on health namely musculoskeletal injury and fatal and nonfatal cardiac events (Institute of Medicine 2007). Cycling can be considered as a moderate type and duration of sport and has lower injury risk than more vigorous types (runners, scholastic athletes) and longer durations of physical activity (Hootman et al. 2001; Parkkari et al. 2004). Exercise has acute cardiac risks as well, but the absolute risk of a cardiac event during exercise seems to be low (Institute of Medicine 2007). Regular physical activity also reduces the acute risk of exercise (Tofler et al. 2006).

Restriction to mortality

We limited the quantitative assessment to mortality. It is difficult to evaluate how the comparison between cycling and car driving would have been if morbidity had been included, because of the lack of solid concentration response relationships for air pollution and physical activity for morbidity outcomes. A meta-analysis reported a consistent positive association between physical activity and health-related quality of life (Bize et al. 2007). The largest cross-sectional study showed that people meeting the recommended levels of physical activity had an adjusted odds ratio of “having 14 or more unhealthy days during the previous months” of 0.4 (95 % CI: 0.36-0.45) over the inactive subjects (Bize et al. 2007). Quality of life may even further improve apart from the increases in life years. Concentrations response functions for air pollutants and morbidity outcomes like hospital admissions are lower than for mortality: in the range of 1% compared to 6% per 10 $\mu g/m^3$ in $PM_{2.5}$ (WHO, 2006). Traffic injuries may differ even more between cyclists and car drivers than fatal accidents (Supplement Material, Table 4), if account for underreporting of especially cyclist accidents is taken. This would reduce the ratio between benefits and risks.

We did not include all stressors in the quantitative evaluation. Cycling contributes to other benefits including reduced emissions of carbon dioxide (CO_2) relevant for reducing climate change; reduced use of physical space related to e.g. parking; reduced traffic noise for city dwellers which may result in less annoyance. We are not aware of exposure studies, nor of health effects studies that have compared traffic noise during transport for cyclists and car drivers.

Suggestions for policy

Our study suggests that policies stimulating cycling likely have net beneficial effects on public health. Policies should be accompanied by safety measures and efforts to limit hazards, e.g. by infrastructural choices (building of cycling lanes away from major roads to limit cyclists’ air pollution exposures) or limitations like a ban on car traffic during school start and end hours near schools. Policies may take the age dependence of the traffic accident risk ratios into account, e.g. by stimulating especially the young to increase cycling. This may however not be the optimal choice for the beneficial effects of cycling.

To assess what traffic policies are effective in promoting a population shift from using cars towards cycling (and walking) is beyond the scope of this paper. A recent review showed that targeted behaviour change programmes can change the behaviour of motivated subgroups, resulting in a 5% shift of all trips at population level in the largest study (Ogilvie et al. 2004). However, effects of similar programmes on the general, less motivated, population are unclear. Those programmes may benefit from taking the public's views into account and learn from good practices (THE PEP: www.healthytransport.com). In particular, perceptions of walking and cycling as dangerous activities are an important barrier to the promotion of active transport (Lorenc et al. 2008).

Summary conclusions

On average the estimated health benefits of cycling were substantially larger than the risks of cycling relative to car driving. For the society as a whole this can be even larger as there will be a reduction in air pollution emissions and eventually less traffic accidents. Policies stimulating cycling are likely to have net beneficial effects on public health especially if accompanied by suitable transport planning and safety measures.

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TABLES

Table 1 Air pollution exposures during cycling and car driving

City	Study design	Pollutant [a]	Mean concentration car (µg/m^3)	Mean concentration cycling (µg/m^3)	Ratio car/cycle	Reference
Amsterdam	Two inner city routes travelled for about one hour in	CO	4833	1730	2.8	van Wijnen et al. 1995
	January and May 1990 (n=55 and 41)	BTEX	332	99	3.4	van Wijnen et al. 1995
Copenhagen	Two cars and two cyclists on a 7.6 km inner city route	BTEX	44	150	0.3	Rank et al. 2001
	in the morning of two days in summer 1998	TSP	44	75	0.6	Rank et al. 2001
London	Three routes from the centre (one central, two to more	$PM_{2.5}$	37	28	1.32	Adams et al. 2001
	outward sections) in July 1999 and Feb 2000. N=96 (cycle trips) and 54 (car trips).	EC	29	18	1.6	Adams et al. 2002
London	Two short (~ 1 km) routes (one heavy traffic, one mixed) travelled in spring 2003 during early morning, lunchtime and afternoon	EC	39	25	1.6	Gegisian 2003
London	Two short (~ 1 km) routes (one heavy traffic, one	$PM_{2.5}$	38	34	1.12	Kaur et al. 2005
	mixed) travelled in spring 2003 during early morning,	UFP	99736	93968	1.06	Kaur et al. 2005
	lunchtime and afternoon	CO	1300	1100	1.18	Kaur et al. 2005
Huddersfield	7-mile journey from village to Huddersfield. Cycle	Abs	7.6	2.7	2.6	Kingham et al. 1998
	along a major highway and a separate bicycle path. Six samples in September / October 1996			6.3	1.2	
11 Dutch cities	Simultaneous cycle and car drives between same start	UFP	25545	24329	1.05	Boogaard et al. 2009
	and end points in afternoon in 11 large Dutch cities. About 12 routes in each city, sampling duration about 3 hours per city. One day per city in autumn 2006	$PM_{2.5}$	49	45	1.11	Boogaard et al. 2009

Arnhem, the Netherlands	Two-hour morning rush hour exposures of cyclists, car and bus passengers on an urban route in a medium sized city.	UFP	40351	44258	0.91	Zuurbier et al. 2010
		$PM_{2.5}$	78	72	1.09	Zuurbier et al. 2010
		Abs	8.8	6.0	1.48	Zuurbier et al. 2010
Mean	Simple mean of ratios applicable studies	$PM_{2.5}$			1.16	
Mean	Simple mean of ratios applicable studies (EC and Abs)	EC			1.65	
Mean	Simple mean of ratios from applicable studies	UFP			1.01	

[a] Abs, absorbance (10^{-5} m), a marker for (diesel) soot; BTEX, sum of benzene, toluene, ethylbenzene and xylene; EC, elemental carbon, equivalent to (diesel) soot; $PM_{2.5}$, mass concentration of particles of less than 2.5 µm in size; TSP, total suspended dust; UFP, ultrafine particle count (cm^{-3}).

Table 2 Epidemiological studies of air pollution exposure in traffic

Study population	Design [a]	Main findings	Comments	Reference
Sixty mild to moderate asthmatic adults in London	Exposure during 2 hour walking in Oxford Street (OS) or Hyde Park (HP). Pre/ and post exposure physiological measurements. Median $PM_{2.5}$ concentration 28 (OS) vs. 11 $\mu g/m^3$ (HP); median EC 7.5 vs. 1.3 $\mu g/m^3$; median UFP 63,700 vs. 18,300 p/cm^3	Asymptomatic decrease in lung function and increase in inflammation after walking in Oxford Street compared to Hyde Park. Changes most consistently associated with EC and UFP. Per 1 $\mu g/m^3$ significant increase in EC decrement in LF of ~1% and increase in exhaled NO (inflammation) of ~2%.	OS has diesel traffic only	(McCreanor et al. 2007)
Subjects (n=691) with a Myocardial Infarction (MI) in Augsburg	Case-crossover study comparing the frequency of participation in traffic in the hours before the MI and a control period (24-72 hours before MI)	RR 2.92 for participation in traffic in the hour before the MI. Increased risk found for all transport means (car, bicycle, public transport)	May be other stressors than air pollution	(Peters et al. 2004)
Nine healthy young US policemen	Physiological measurements before and after 8-hour work shift. Average in-vehicle $PM_{2.5}$ 24 $\mu g/m^3$	Significant increases of heart rate variability, ectopic beats, blood inflammatory and coagulation markers and red blood cell volume. Per 10 $\mu g/m^3$ $PM_{2.5}$ effect on C-reactive protein +32%, neutrophils +6%, von Willebrand factor +12% and ectopic beats +20%.		(Riediker et al. 2004)
Twelve healthy young subjects	Physiological measurements before and after 1-hour cycling trip from city center to university in Utrecht.	Statistically non-significant 1-3% decrements in lung function per to $1*10^{-5}$ m soot concentration and a 15% increase in exhaled NO per 38,000 $particles.cm^{-3}$		(Strak et al. 2010)

[a] EC, elemental carbon; UFP, ultrafine particles, MI, myocardial infarction

Table 3 Potential mortality impact of cycling compared to car driving, for 0.5 and 1 hour commute estimated for $PM_{2.5}$ and Black Smoke [a]

Travel mode	Duration of travel (hr / day)	Concentration $PM_{2.5}$ / BS ($\mu g/m^3$)	Inhaled dose (µg /day)	Total dose [b] for car or bicycle (µg/day)	Equivalent change in $PM_{2.5}$ or BS ($\mu g/m^3$)	RR mortality, equal toxicity[c]	RR mortality, traffic 5x more toxic
				$PM_{2.5}$			
Car	0.5	40.0	12.0	246			
Cycle	0.5	34.5	22.8	257	0.9	1.005	1.026
Car	1.0	40.0	24.0	252			
Cycle	1.0	34.5	45.5	274	1.8	1.010	1.053
				Black Smoke			
Car	0.5	30.0	9.0	126			
Cycle	0.5	18.2	12.0	129	0.2	1.001	1.006
Car	1.0	30.0	18.0	132			
Cycle	1.0	18.2	24.0	138	0.5	1.002	1.012

[a] Supplement Material, Table 2 has details on calculations and assumptions.
[b] Total dose includes other time periods.
[c] RR for cycling versus car driving.

Table 4 Traffic deaths per age category per billion passenger km by bicycle and by car in the Netherlands [a] (CBS, 2008)

Age category	Bicycle	Car	Ratio
<15	4.9	0.6	8.6
15-20	5.4	7.4	0.7
20-30	4.2	4.6	0.9
30-40	3.9	2.0	2.0
40-50	6.6	1.0	6.9
50-60	9.6	1.2	7.9
60-70	18.6	1.6	11.7
70-80	117.6	7.6	15.4
>80	139.6	8.1	17.1
Total average (all ages)	12.2	2.2	5.5
Total average (20 – 70)	8.2	1.9	4.3

[a] Estimated as age and traffic mode specific number of traffic deaths divided by amount of kilometres driven per age and traffic mode in the Netherlands for the year 2008.

Table 5 Potential impact of physical activity on all cause mortality in various reviews [a] and cohort studies

	Source	Definition of physical activity	Relative risk [b]	Comments
REVIEWS	(Lee and Skerrett 2001)	Meeting moderate physical activity recommendation (1000 kcal/week)	0.70 – 0.80	Review, excluding papers examining only two levels of physical activity
	(Kesaniemi et al. 2001)	Expending of 1000 kcal/week	0.70	Based on a symposium. Invited experts reviewed the existing literature.
	(Bauman 2004)	Meeting physical activity recommendation	0.70	Review of peer-reviewed studies published between 2000-2003
	(Bucksch and Schlicht 2006)	Different definitions of physical activity:	0.70-0.87 (moderate) 0.46-0.92 (vigorous)	Review.
	(Warburton et al. 2006)	Meeting physical activity recommendation	0.65 – 0.80	Review.
	(Vogel et al. 2009)	Different definitions including moderate exercise (4100-7908 kJ/week), vigorous exercise, and different distance walked.	0.50-0.77	Review of adult cohort studies with a mean age over 60 years.

Table 5 continued

IND. STUDIES ON CYCLING	(Andersen et al. 2000)	Cycling to work for 3 hours per week	0.55-0.72	Based on a Danish cohort. Adjusted for leisure time physical activity (among others).
	(Hu et al. 2004)	Walking and cycling to work	0.71-0.79	Based on a Finnish cohort study among subjects with Type 2 diabetes. Estimates without adjusting for other domains in Physical Activity.
	(Matthews et al. 2007)	Cycling to work (MET-hours/day)	0.66 – 0.79	Based on a Chinese women cohort in Shanghai. Adjusted for other physical activity
	Overall summary		0.50 – 0.90	

[a]. Reviews used are often overlapping (reviewing the same evidence).

[b] comparing physically active to physically less active

Table 6 Summary table of impact of the modal shift on all-cause mortality for subjects shifting from car to bicycle

Stressor	Relative risk	Gain in life years[a]	Gain in life days / months per person[a]
Air pollution	1.001 – 1.053	- 1,106 to -55,163 (-28,135)	-0.8 to -40 days (-21 days)
Traffic accidents	0.996to 1.010[b] – 0.993 to 1.020[b]	- 6,422 to - 12,856 (-9639)	-5 to -9 days (-7 days)
Physical activity	0.500 – 0.900	564,764 to 111,027 (337,896)	14 to 3 months (8 months)

[a] applied to the 500,000 subjects making the shift aged 18 – 64 with standard life table calculations (Miller and Hurley 2003). In parentheses is the average of the life gain (a minus sign implies a loss of life years)

[b] We have applied age group specific relative risks in the life table calculations, for the range see Supplement Material, Table 5. The 0.996–1.010 is for the 7.5 km distance; the 0.993 – 1.020 for the 15 km distance

Supplement Material

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Do The Health Benefits Of Cycling Outweigh The Risks?

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Environmental Health Perspective, 2010

Supplement Material, Table 1 Human controlled exposure studies of traffic-related particulate matter air pollution

Study population	Exposure	Main findings	Ref.
Fifteen healthy young subjects	1 hour with intermittent exercise to 300 µg/m^3 diesel exhaust	No changes in lung function directly after exposure but marked systemic and pulmonary inflammation six hours after exposure, e.g. 3-4 fold increase in neutrophils in bronchial tissue and 1.5 fold increase of neutrophils in blood.	Salvi, 1999; Salvi 2000
Ten young healthy subjects	2 hour at rest to 200 µg/m^3 diesel exhaust	No changes in lung function, HR, BP and inflammation markers in blood. Significant increase in exhaled CO indicating oxidative stress (+50%), neutrophils (+28%) and other markers of airway inflammation in sputum 4 hr after exposure.	Nightingale, 2000
Healthy subjects and mild asthmatics	2 hour to 108 µg/m^3 diesel exhaust particles	No change in lung function. Increase in airway resistance (4.1% in healthy subjects and 6.5% in asthmatics). Increase in airway inflammation in healthy subjects (+40% for neutrophils), not found in asthmatics. Increase in cytokines (IL-6, Il-8) in healthy subjects and IL-10 in asthmatics.	Stenfors, 2004
Thirty health young subjects	1 hour with intermittent moderate exercise to 300 µg/m^3 diesel exhaust	No change in blood inflammatory markers, 34% reduction of fibrinolytic capacity (tissue plasminogen activator) and reduction of response to vasodilator (smaller increase in forearm blood flow, vasomotor function). At 24-hour vasomotor function changes persisted and systemic inflammation was found (Il-6, TNF-α).	Mills, 2005; Törnqvist, 2007
Twenty men with a prior myocardial infarction	1 hour with intermittent exercise to 300 µg/m^3 diesel exhaust	Asymptomatic increase in indicators of myocardial ischemia (doubling of ST-segment depression and ischemic burden) and 35% reduction of fibrinolytic capacity possibly resulting in thrombosis. No change in inflammation markers and vasomotor function.	Mills, 2007
Twenty-three healthy subjects	2 hour at rest to 147 ± 27 µg/m^3 $PM_{2.5}$ (CAP) + 121 ± 3 ppb ozone. Mean OC 25 ± 12 µg/m^3	Increase of diastolic blood pressure of ~10% and no changes in HR. Associations especially with OC (traffic) and not with total $PM_{2.5}$.	Urch, 2005
Fifteen healthy volunteers	2 hour with intermittent exercise to 100 µg/m^3 diesel exhaust particles	Increased bronchial but not alveolar inflammation indicated by increased neutrophil and mast cell counts and inflammation markers IL-8 and MPO in bronchial wash. Increase in anti-oxidants urate and gluthathione in alveolar lavage. All health effects are for 18 hr post-exposure.	Behndig, 2006
Twelve healthy and twelve asthmatic subjects	2 hour with intermittent exercise to on average 174µg/m^3 $PM_{2.5}$ (CAP)	No changes in lung function or routine hematologic measurements. Both groups showed decreases of columnar cells in postexposure induced sputum, slight changes in mediators of blood coagulability and systemic inflammation, and modest increases in parasympathetic stimulation of heart rate variability. Systolic blood pressure decreased in asthmatics and increased in healthy subjects. Cardiovascular (but not respiratory) symptoms increased slightly in both groups.	Gong, 2003
Twenty CHD and twenty healthy subjects	1 hour to 50 µg/m^3 carbon particles and 200 ppb SO_2	No effect was found on systemic inflammation and heart rate variability.	Routledge, 2006

Seventeen healthy and fourteen asthmatic subjects	2 hour with intermittent exercise to on average 145,000 p/cm^3 ultrafine particles (CAP)	Small decrements of lung function, oxygen saturation in blood and heart rate variability in both healthy and asthmatic volunteers	Gong, 2008
Fourteen young healthy subjects	1 hour with intermittent exercise to 300 µg/m^3 diesel exhaust particles followed by 0.2 ppm ozone 5 hrs later	Significant increase in airway inflammation as indicated by neutrophils, macrophages and eosinophils in bronchial wash, but not alveolar lavage. The study documents interaction between diesel and ozone exposure.	Bosson, 2008
Twenty healthy subjects	2 hour to 350 µg/m^3 diesel exhaust 1 hour to 350 µg/m^3 diesel exhaust	Increased platelet activation and thrombus formation, which may lead to cardiac events such as MI in patients	Lucking, 2008
Ten healthy young subjects	1 hour in rest to 300 µg/m^3 diesel exhaust	Physiological changes observed in electroencephalography (EEG), indicative of a general cortisol stress response.	Crüts, 2008
Twelve CHD and twelve healthy subjects	2 hour intermittent moderate exercise to 190 ± 37 µg/m^3 $PM_{2.5}$ (CAP) and 99,400 p/cm^3 UFP	No effect on vasomotor function, BP, HR, fibrinolytic function and systemic inflammation, though small increases of platelets and monocytes were found. About four-fold increase in 8-isoprostane in exhaled breath condensate (oxidative stress) in 8 healthy subjects. Likely due to composition of PM (90% sea salt)	Mills, 2008

Note: in all studies post-pre exposure effects on health were compared with filtered air exposure of the same exercise and duration.
BHR,bronchial reactivity test; HR, heart rate; BP, blood pressure; CAP, concentrated ambient particles; OC, organic carbon fraction of $PM_{2.5}$; CHD, coronary heart disease; UFP, ultrafine particles; MI, myocardial infarction.

Supplement Material, Table 2a **Calculation of the potential mortality impact of cycling compared to car driving, under various assumptions of the exposure in the car, the increase in inhaled dose due to cycling, and the relative risk to calculate the mortality impact for $PM_{2.5}$**

Activity	Minute ventilation (l/min.)[a]	Duration (hr/day)	Concentration $PM_{2.5}$ ($\mu g/m^3$)[b]	Inhaled dose (μg/day)[c]	Total dose (μg/day)[d]	Ratio of total dose bicycle/car	Mean $PM_{2.5}$ ($\mu g/m^3$)[e]	Equivalent change in $PM_{2.5}$ ($\mu g/m^3$)[f]	RR mortality, equal toxicity[g]	RR mortality, traffic 5x more toxic
Half hour commute										
Sleep	5.0	8.0	20.0	48.0						
Rest	10.0	15.5	20.0	186.0						
Car	10.0	0.5	30.0	9.0	243					
Cycle	22.0	0.5	25.9	17.1	251	1.03	20.2	0.7	1.004	1.020
Sleep	5.0	8.0	20.0	48.0						
Rest	10.0	15.5	20.0	186.0						
Car	10.0	0.5	40.0	12.0	246					
Cycle	22.0	0.5	34.5	22.8	257	1.04	20.4	0.9	1.005	1.026
One hour commute										
Sleep	5.0	8.0	20.0	48.0						
Rest	10.0	15.0	20.0	180.0						
Car	10.0	1.0	30.0	18.0	246					
Cycle	22.0	1.0	25.9	34.1	262	1.07	20.4	1.3	1.008	1.040
Sleep	5.0	8.0	20.0	48.0						
Rest	10.0	15.0	20.0	180.0						
Car	10.0	1.0	40.0	24.0	252					
Cycle	22.0	1.0	34.5	45.5	274	1.09	20.8	1.8	1.010	1.053

Supplement Material, Table 2b **Calculation of the potential mortality impact of cycling compared to car driving, under various assumptions of the exposure in the car, the increase in inhaled dose due to cycling, and the relative risk to calculate the mortality impact for BS**

Activity	Minute ventilation (l/min.)[a]	Duration (hr/day)	Concentration BS (μg/m^3)[b]	Inhaled dose (μg/day)[c]	Total dose (μg/day)[d]	Ratio of total dose bicycle/car	Mean BS (μg/m^3)[e]	Equivalent change in BS (μg/m^3)[f]	RR mortality, equal toxicity[g]	RR mortality, traffic 5x more toxic
Half hour commute										
Sleep	5.0	8.0	10.0	24.0						
Rest	10.0	15.5	10.0	93.0						
Car	10.0	0.5	20.0	6.0	123					
Cycle	22.0	0.5	12.1	8.0	125	1.02	10.2	0.2	1.001	1.004
Sleep	5.0	8.0	10.0	24.0						
Rest	10.0	15.5	10.0	93.0						
Car	10.0	0.5	30.0	9.0	126					
Cycle	22.0	0.5	18.2	12.0	129	1.02	10.4	0.2	1.001	1.006
One hour commute										
Sleep	5.0	8.0	10.0	24.0						
Rest	10.0	15.0	10.0	90.0						
Car	10.0	1.0	20.0	12.0	126					
Cycle	22.0	1.0	12.1	16.1	130	1.03	10.4	0.3	1.002	1.008
Sleep	5.0	8.0	10.0	24.0						
Rest	10.0	15.0	10.0	90.0						
Car	10.0	1.0	30.0	18.0	132					
Cycle	22.0	1.0	18.2	24.0	138	1.05	10.8	0.5	1.002	1.012

N.B.:Values are rounded.

[a] Typical values for minute ventilation at sleep and rest assumed as 5 and 10 l/min (0.3 m^3/h and 0.6 m^3/h respectively). Minute ventilation for car drivers is assumed to be equivalent to that at rest 10 l/min (0.6 m^3/h). Minute ventilation for cyclists is assumed to be 2.2 times the estimate for drivers (22L/min or 1.32 m^3/h) based on information reported in van Wijnen et al. 1995 (minute ventilation of cyclists 2.3 times that of drivers) and Zuurbier et al. 2009 (minute ventilation of cyclists 2.1 times that of drivers).

[b] Concentrations of $PM_{2.5}$ and BS during sleep and rest are assumed to be equivalent to typical European urban background values (Putaud et al. 2010; Schaap and van de Gon, 2007) of 20µg/m^3 and 10µg/m^3, respectively. Concentrations during driving are assumed to be either 1.5 times or two times the background concentration for $PM_{2.5}$ (scenario1: 30, scenario 2: 40µg/m^3) and 2 times or 3 times the background concentration for BS (scenario 1: 20, scenario 2: 30µg/m^3) based on Zuurbier et al. 2010. Concentrations of $PM_{2.5}$ and BS during cycling are assumed to be 0.862 and 0.606 times those estimated for drivers based on information summarized in Table 1 (scenario 1: 25.9µg/m^3 and 12.1µg/m^3 for $PM_{2.5}$ and BS, respectively; scenario 2: 34.5µg/m^3 and 18.2µg/m^3 for $PM_{2.5}$ and BS, respectively).

[c] Inhaled dose (µg/day) = minute ventilation (m^3/h) * duration (h/day) * concentration (µg/m^3)

[d] Total dose (µg/day) = Inhaled dose during sleep + rest + driving or cycling.

[e] Time-weighted average $PM_{2.5}$ or BS exposure over a 24-hour period for drivers (baseline situation).

[f] Calculated as the fractional difference of the total dose for cycling versus car driving multiplied by the time weighted average $PM_{2.5}$ concentration. For example, assuming a half hour commute under exposure scenario 1, the equivalent change in $PM_{2.5}$ = [(251µg/day / 243µg/day) - 1] * 20.2µg/m^3 = 0.7µg/m^3, meaning that the added exposure in cyclists is equivalent to breathing an average $PM_{2.5}$ concentration that is 0.7µg/m^3 higher than the average concentration to which drivers are exposed.

[g] RR, Relative Risks, estimated as: EXP[LN(1.06)*(equivalent $PM_{2.5}$ change /10)], where 1.06 is the average adjusted relative risk of all cause mortality for a 10 µg/m^3 change in $PM_{2.5}$ concentration derived from the American Cancer Society study (Pope et al. 2002) and as EXP[LN(1.05)*(equivalent BS change /10)] where 1.05 is the average adjusted relative risk of natural cause mortality (i.e., all deaths excluding accidents and murders, ICD-9 > 800) for a 10 µg/m^3 change in BS based on Beelen et al. 2008.

[h] Estimates assuming that traffic exposures are 5 times more toxic than background exposures are estimated as EXP[(5*(LN(1.06))*(equivalent $PM_{2.5}$ change /10)] for PM2.5 and as EXP[(5*LN(1.05))*(equivalent BS change /10)] for BS.

Supplement Material, Table 3 **Injuries and fatalities plus hospital admissions per age category per billion passenger kilometres by bicycle and by car within urban areas in the Netherlands (van Boggelen 2005).**

Age	**Injuries**			**Fatalities and hospital admissions**		
	Bicycle	car	Risk ratio	Bicycle	car	Risk ratio
0-11	545	80	6,8	115	12	9,5
12-17	1164	349	3,3	199	72	2,8
18-24	1019	903	1,1	198	197	1,0
25-29	826	434	1,9	150	86	1,7
30-39	614	267	2,3	118	51	2,3
40-49	642	196	3,3	149	33	4,4
50-59	780	173	4,5	213	33	6,4
60-74	1018	204	5,0	329	52	6,3
75+	2567	449	5,7	1077	147	7,4
Total	***882***	***280***	***3,2***	***205***	***56***	***3,7***

Supplement material, Table 4 Mortality rates for being involved in a fatal traffic accident per billion kilometers traveled in the Netherlands, excluding motorways (European Commission, 1999).

Age category	Bicycle	Car
12-14	16.8	-
15-17	18.2	-
18-24	7.7	33.5
25-29	8.2	17.0
30-39	7.0	9.7
40-49	9.2	9.7
50-59	17.2	5.9
60-64	32.1	10.4
> 64	79.1	39.9
Total [a]	21.0	20.8

[a] The average total risk is biased against cyclists because two (less experienced, less cautious) age groups which do not exist among motorists are taken into consideration. Non-weighed rates for the 18-64 yr old are 13.6 and 14.4 for cyclists and car drivers respectively. The rates include the risk that car drivers present to other road users (pedestrians, cyclists)

Supplement Material, Table 5 Analysis of life years gained /lost from shifting to bicycle use for a 7.5 km distance travelled per age group

Stressor	Age category	Baseline mortality rate[a]	Mean Relative risk	Gain in life years [a]	Loss or gain in days / months per person*
Air pollution	18-39	238	1.03	-4153	-3 days
	40-64	1932	1.03	-26 019	-19 days
	65+	22 660	1.03	-83 788	-2 months
Traffic accidents	18-39	238	Age 18-29: 0.996 Age 30-39: 1.009	-806	-0.6 days
	40-64	1932	Age 40-49: 1.010 Age 50-59: 1.005 Age 60-64: 1.005	-4731	-3 days
	65+	22 660	Age 65-69: 1.004 Age 70-79: 1.010 Age 80+: 1.003	-14 532	-11 days
Physical activity	18-39	238	0.70	41 580	1 month
	40-64	1932	0.70	263 517	6 months
	65+	22 660	0.70	1 062 527	2 years

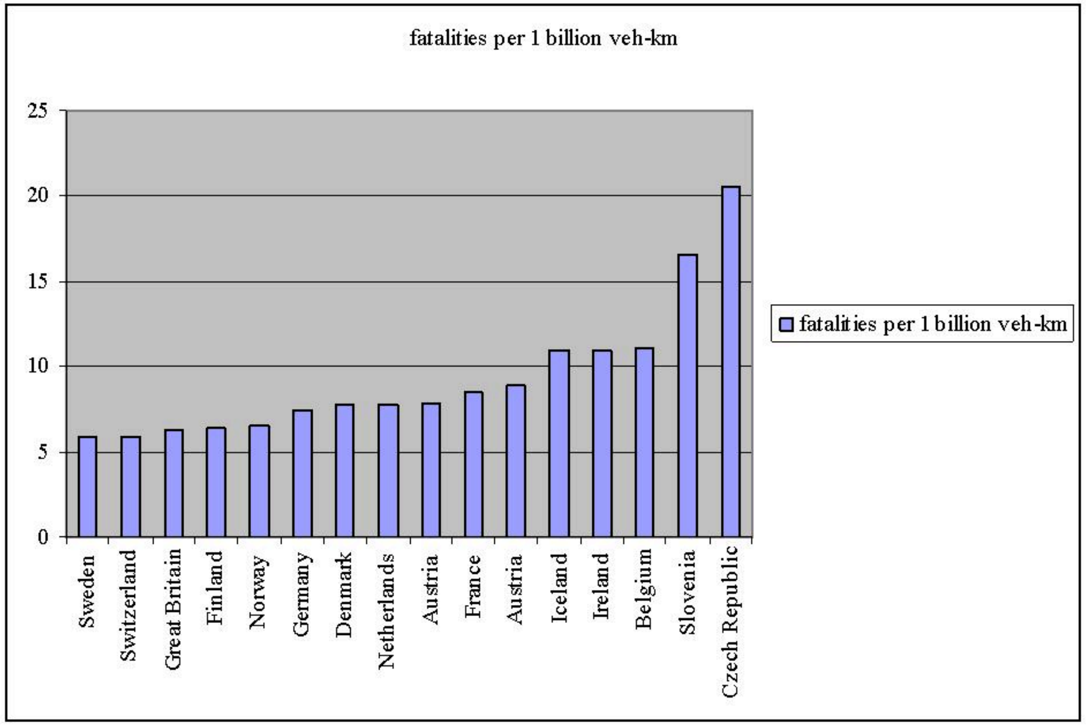
Values are rounded. Estimates are presented for the mean RRs in table 7. Values can be compared to the central estimate in table 6 in the main text. [a] applied to 500,000 subjects with different age categories with standard life table calculations (Miller and Hurley 2003). A minus sign implies losses

Supplement Material, Table 6 **Percentage of trips taken by walking and cycling in European countries and USA (Bassett et al., 2008).**

Country	Year	Walking	Cycling
Austria	2005	21	4
Belgium	1999	16	8
Denmark	2003	16	15
Finland	2005	22	9
France	1994	19	3
Germany	2002	23	9
Latvia	2003	30	5
Netherlands	2006	22	25
Norway	2001	22	4
UK	2006	24	2
USA	2001	9	1
Sweden	2006	23	9

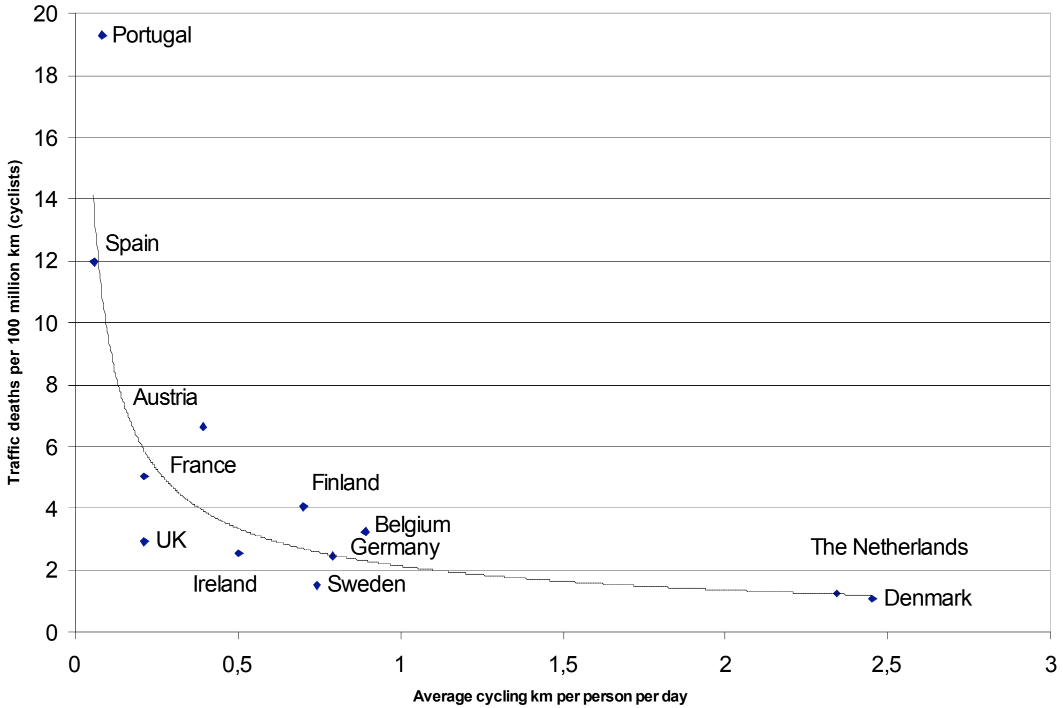
Walking and cycling rates to differ significantly between various countries. The table suggests that in most countries, especially in the USA, there is ample room for increasing physical activity levels by walking and cycling.

Supplement Material, Figure 1 Traffic deaths per 1 billion vehicle-km (2006).



Adapted from IRTAD-OECD http://www.internationaltransportforum.org.

Supplement Material, Figure 2 Relationship between average distance cycled per person per day and fatal traffic accident rate of cyclists (per 100 million km)



Adapted from IRTAD-OECD http://www.internationaltransportforum.org. and van Hout 2007.