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Cycling as a Part of Daily Life: A Review of Health Perspectives

THOMAS GÖTSCHI^{*S} , JAN GARRARD^{**} AND
BILLIE GILES-CORTI[†]

**Epidemiology, Biostatistics and Prevention Institute, Physical Activity and Health Unit, University of Zurich, Seilergraben 49, 8001 Zürich, Switzerland; **School of Health and Social Development, Deakin University, 221 Burwood Highway, Burwood, Victoria 3125, Australia;*

†Melbourne School of Population and Global Health, The University of Melbourne, Parkville, Victoria 3010, Australia.

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ABSTRACT Health aspects of day-to-day cycling have gained attention from the health sector aiming to increase levels of physical activity, and from the transport and planning sector, to justify investments in cycling. We review and discuss the main pathways between cycling and health under two perspectives — generalizable epidemiological evidence for health effects and specific impact modeling to quantify health impacts in concrete settings. Substantial benefits from physical activity dominate the public health impacts of cycling. Epidemiological evidence is strong and impact modeling is well advanced. Injuries amount to a smaller impact on the population level, but affect crash victims disproportionately and perceived risks deter potential cyclists. Basic data on crash risks are available, but evidence on determinants of risks is limited and impact models are highly dependent on local factors. Risks from air pollution can be assumed to be small, with limited evidence for cycling-specific mechanisms. Based on a large body of evidence, planners, health professionals, and decision-makers can rest assured that benefits from cycling-related physical activity are worth pursuing. Safety improvements should be part of the efforts to promote cycling, both to minimize negative impacts and to lower barriers to cycling for potential riders.

Introduction

Cycling as a means for day-to-day travel has gained attention from the transport and environmental sectors for a number of advantages over motorized travel. More recently, the health sector has begun to embrace cycling for its potential to increase physical activity levels in children (Trapp et al., 2011), adults (Beenackers et al., 2012; Craig et al., 2012; Rissel et al., 2010; Titze, Stronegger, Janschitz, & Oja, 2008; Wanner, Gotschi, Martin-Diener, Kahlmeier, & Martin, 2012), and older adults (Heesch, Giles-Corti, & Turrell, 2014).

Regular physical activity provides a wide range of health benefits (Lee et al., 2012; Physical Activity Guidelines Advisory Committee, 2008). The World

^SCorresponding author. Email: thomas.goetschi@uzh.ch

Health Organization recommends a minimum of 150 minutes of moderate physical activity per week (WHO, 2010). But despite substantial benefits, increasing proportions of western and other populations fail to achieve recommended levels of activity. Integrating cycling into daily routines provides a promising approach to increase physical activity, given the many people who spend 30 minutes and more commuting daily, yet struggle to find the extra half-hour to exercise (Bauman et al., 2012; Trost, Owen, Bauman, Sallis, & Brown, 2002). The combination of mobility and physical activity is also cheap and does not require major skills, making it suitable for large segments of the population.

Nonetheless, cycling has remained a marginal factor in both transport and health policies, with only few exceptions. Reasons for this may in part be the perceived risks of crashes and exposure to air pollution associated with (urban) cycling, the generally small mode share of cycling (with few exceptions), various socio-psychological and environmental barriers, or a simple lack of prioritization in policy and planning, among others (Pucher & Dijkstra, 2003; Pucher, Dill, & Handy, 2010; Winters, Davidson, Kao, & Teschke, 2011). One may argue that understanding the implications of cycling for (public) health is an important foundation for policy, planning, and decision-making related to cycling, and equally so for the individual decision to cycle.

This narrative review aims to highlight issues and key findings of relevance for a better understanding of health aspects of day-to-day cycling. The focus is on types and purposes of cycling that are the targets of cycling promotion in the general population, such as approaches to sustainable transport, livable communities, or physical activity promotion. This includes cycling for recreation, in the sense of leisurely or moderate-to-vigorous rides with the primary purpose of recreation, fitness, or health, but explicitly excludes cycling for sports or competitive cycling, although various health aspects apply to it equally.

Health effects of cycling can be both positive (benefits) and negative (risks). The main pathway for health benefits from cycling is physical activity. Other beneficial pathways include improvements of quality of life through mobility and access gained through cycling. Some beneficial outcomes, such as improved cognitive function or reduced risk of depression, may reflect a mix of all these pathways. Finally, there are indirect health benefits of reduced motor vehicle use when cycling trips replace car trips (e.g. reduced air and noise pollution, and increased social engagement in more livable communities).

The main negative pathways are crash risks and the risk of increased exposure to air pollution while riding in motorized traffic.

This review scopes out key publications around these main pathways to present a structured overview, methodological insights, and selected key issues we consider important to understand the links between cycling and health. Health benefits and risks of cycling are complex, context dependent, and often under-researched. Consequently, it is not always possible to come to definitive conclusions. The review of the literature is not systematic or comprehensive, but numerous references to original research as well as systematic reviews are provided to facilitate more in-depth inquiries on specific aspects. Two main perspectives are explored.

The first perspective focuses on *epidemiological evidence* of effects of cycling on the most relevant health outcomes. These studies describe the relationships between clearly defined exposures (cycling) and outcomes (health endpoints), such as the magnitude and shape of the association that can be expected to be

generalizable to other populations. This evidence is useful to determine whether cycling is 'healthy' or 'risky', but it is not sufficient on its own to inform public policy on the value of promoting cycling at the population level.

The second perspective focuses on *health impact modeling* to quantify the magnitude of impacts, such as the prevention of diseases, by specific policies or scenarios in realistic settings, namely in clearly defined populations and over defined periods of time. Epidemiological evidence is at the core of health impact modeling, but in addition health impact models apply their own set of methods.

Health Pathways Related to Cycling

The main health pathways are described in the order of magnitude of impacts, based on findings from health impact studies (Mueller et al., 2015). These indicate that on a population level, benefits from physical activity from cycling outweigh risks from crashes and air pollution as well as indirect effects from reductions in motor vehicle use (de Hartog, Boogaard, Nijland, & Hoek, 2010; Rabl & De Nazelle, 2012; Rojas-Rueda, de Nazelle, Teixidó, & Nieuwenhuijsen, 2013).

Physical Activity from Cycling

Epidemiological evidence on health effects of physical activity from cycling. From a physiological point of view, physical activity from cycling is equivalent to other activities of equal intensity, duration, and frequency, such as, manual labor, sports, exercise, or walking.

In 2008, the US Physical Activity Guidelines Advisory Committee issued an exhaustive report summarizing the evidence of health effects of physical activity based on systematic reviews of hundreds of epidemiological studies (Physical Activity Guidelines Advisory Committee, 2008). Overall physical activity and leisure time physical activity have been associated with risk reduction for a number of diseases and mortality. In addition, various intermediate health indicators, such as cardiorespiratory fitness, obesity, or biomarkers, show beneficial associations with physical activity. Benefits have been observed in the general population, as well as in children and youth, in the elderly, in different ethnicities, and in overweight and obese subjects. Table 1 lists the health outcomes with strong evidence for beneficial associations with physical activity.

From a public health perspective, the focus is clearly on long-term health effects, while more immediate effects on, for example, weight control and (mental) well-being may play a larger role for individuals' decisions to bike (Gatersleben & Haddad, 2010; Garrard, Rissel, & Bauman, 2012).

Estimated risk reductions between the most active and the least active subjects are substantial, that is, about 30% for all-cause mortality; 20–35% for cardiovascular disease, coronary heart disease, and stroke; between 30% and 40% for type 2 diabetes; about 30% for colon cancer; and about 20% for breast cancer (Physical Activity Guidelines Advisory Committee, 2008). A number of meta-analyses have shown a nonlinear dose–response relationship between physical activity and health, with the least active individuals benefiting the most from any given dose of physical activity (Carnethon, 2009; Harriss et al., 2009; Lee & Skerrett, 2001; Samitz, Egger, & Zwahlen, 2011; Sattelmair et al., 2011; Woodcock, Franco, Orsini, & Roberts, 2011). For example, a meta-analysis of 22 cohort studies of

Table 1. Health effects of physical activity in adults

Physical activity has beneficial effects on ...	Physical activity reduces the risk of ...
Life expectancy	Coronary heart disease
Cardiorespiratory fitness	High blood pressure
Musculoskeletal fitness	Stroke
Healthy body weight	Type 2 diabetes
Healthy body composition	Metabolic syndrome
Bone health	Breast and colon cancer
Sleep quality	Depression
Quality of life	
Independent mobility*	Falls*
Cognitive function*	

Note: For the listed health endpoints scientific evidence is strong (moderate for sleep quality and quality of life). Additional benefits in elderly people are marked with an (*). Based on Physical Activity Guidelines Advisory Committee (2008).

adults found that compared with no physical activity, 2.5 hours/week of moderate-intensity activity (equivalent to 30 min daily on 5 days a week) was associated with a 19% reduction in mortality risk, and 7 hours/week of physical activity (i.e. one hour daily) with a 24% reduced mortality risk (Woodcock et al., 2011).

The World Health Organization recommends that, “adults should do at least 150 minutes of moderate-intensity aerobic physical activity throughout the week or do at least 75 minutes of vigorous-intensity aerobic physical activity throughout the week, or an equivalent combination of moderate- and vigorous-intensity activity” (WHO, 2010).

Despite the consistent evidence for benefits of physical activity, and the fact that cycling contributed to physical activity in many of these studies, they usually do not provide cycling-specific effect estimates. However, cycling is generally at least of moderate intensity, hence one can assume that their findings equally apply to cycling.

A relatively small, but growing number of studies specifically on the health effects of cycling have been conducted. Findings are mostly consistent with effects of overall physical activity, although inconclusive results are more common, depending on the health outcome and population studied, and how cycling is measured (Kelly et al., 2014; Oja et al., 2011; Saunders, Green, Petticrew, Steinbach, & Roberts, 2013).

The first major cohort study reporting cycling-specific effect estimates was conducted in Copenhagen, Denmark (Andersen & Cooper, 2011; Andersen, Schnohr, Schroll, & Hein, 2000). In a sample of approximately 20 000 study participants, almost 7000 reported commuting by bike. Adjusted for other physical activity and various risk factors, cycling to work was associated with a 28% decrease in all-cause mortality risk. These findings were later confirmed by Matthews et al. (2007) in a large cohort of Chinese women, which found a 21% reduction in all-cause mortality for 3.5 hour of cycling per week, compared to none.

More recently, Kelly et al. (2014) conducted a meta-analysis including seven cohort studies on cycling which adjusted for physical activity from other domains and collectively observed over 2 million person-years. For a cycling level corresponding to WHO recommendations for physical activity (i.e. 150 minutes or 11.25METh/week¹), they found a reduction of 10% in risk of all-

cause mortality, compared with no cycling. They also estimated the dose–response relationship of cycling, suggesting that physical activity benefits per unit of cycling are about twice as high for the first one or two hours of cycling per week, compared with significantly more time spent cycling (see [Figure 1](#)). Others have found similarly shaped dose–response curves for walking or general physical activity (Woodcock et al., 2011).

Because of the nonlinear dose–response relationship, interpreting the effect estimates of physical activity from cycling (or any physical activity sub-domain) requires caution. When applied to individuals outside of the study population, the effect of cycling will depend on the level of physical activity subjects accrue through other activities (among various other factors). However, few studies have collected data on both cycling and overall (or other) physical activity.

Modeling health impacts of cycling-related physical activity. Health impact models aim to quantify benefits and risks of a certain level of or change in cycling in a specific population, over a defined period of time, and in as realistic a setting as possible. Assessments can look at the status quo, retrospective or prospective changes over time, before and after comparisons related to specific measures or policies, or purely hypothetical scenarios.

For example, in a cost–benefit analysis of new cycle infrastructures in Norway, Saelensminde (2004) assumed benefits from physical activity worth approx. US\$1000 annually for those who became ‘moderately more active’ through cycling. In a scenario calculation for Barcelona, Spain, Rojas-Rueda et al. (2013) estimated that if 20% of car trips (94 460 trips/day) would be shifted to cycling, 15 incidences of cardiovascular disease and 45 cases of type 2 diabetes would be avoided annually among those shifting from driving to cycling. In a compara-

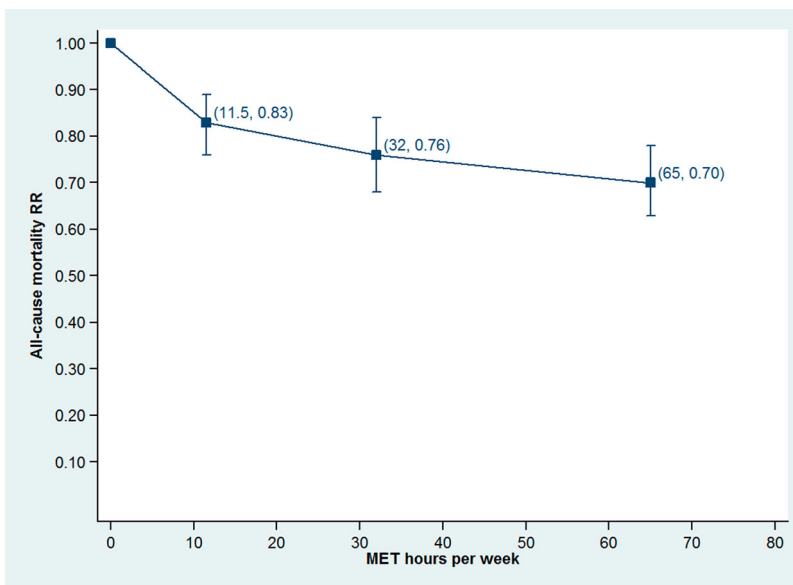


Figure 1. Dose–response relationship between cycling and relative risk (RR) of all-cause mortality, based on seven cohort studies including nearly 2 million person-years (Figure originally published by BioMed Central in (Kelly et al., 2014).

tive risk assessment of hypothetical greenhouse gas reduction policies, Woodcock et al. (2009) found that in London, UK, and Delhi, India, increases in active travel would lead to much larger health benefits (approx. 10 000 disability adjusted life years per 1 million people and year) than shifts to lower emission motor vehicles. Finally, in a recent systematic review of health impact models of active transport, Mueller et al. (2015) found that the vast majority of studies reported substantially higher benefits from physical activity, compared to risks. Woodcock, Tainio, Cheshire, O'Brien, and Goodman (2014) point out, however, that this pattern may not always hold true when looking at selected population segments in which health benefits are lower and crash risks may be higher (e.g. in young people). The comparison and interpretation of such findings is challenged by the various assumptions necessary to translate epidemiological evidence into specific impacts. Figure 2 illustrates key steps common in health impact modeling for cycling.

A main challenge lays in scaling effect estimates from epidemiologic studies (i.e. relative risks) to the impact model setting of interest. The World Health Organization's Health Economic Assessment Tool (HEAT) for walking and cycling (Kahlmeier et al., 2011; WHO, 2011) applies a log-linear scaling function and uses a cycling-specific relative risk (exposure measured as cycling) (Andersen et al., 2000; Kelly et al., 2014). This tool, designed for transport planners without health background, provides a simple way to estimate avoided premature deaths due to physical activity from walking or cycling.

In more sophisticated models, physical activity-based relative risks are used (Woodcock et al., 2009; Woodcock, Givoni, & Morgan, 2013). The intensity of physical activities is measured as metabolic equivalents of tasks (METs). Reference values for various activities are available from the compendium of physical activities (Ainsworth et al., 2011). It places most cycling at least in the 'moderate inten-

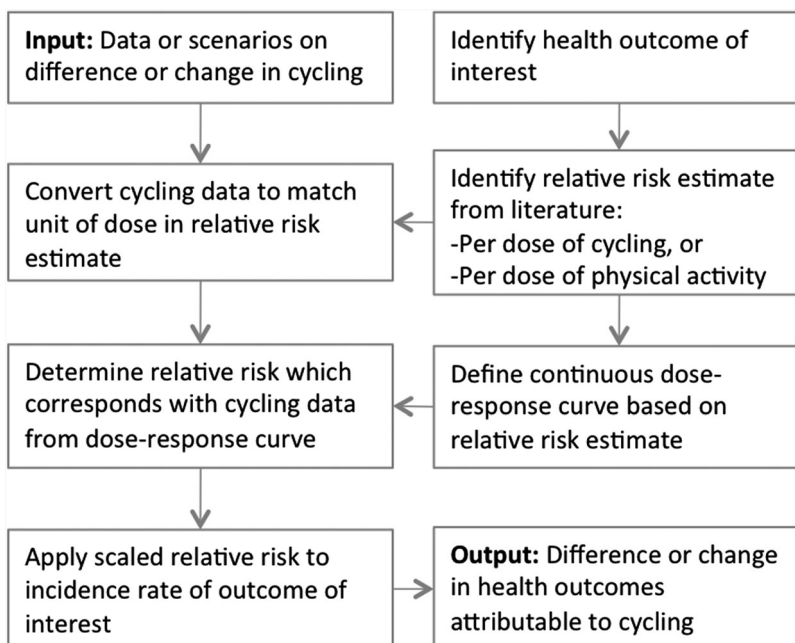


Figure 2. Generic flowchart of key steps of health impact modeling for physical activity from cycling.

sity' category of around 5–8 METs. If population data on physical activity and cycling are available, nonlinear dose–response functions can be applied, where subjects with lower physical activity will benefit more from additional physical activity from cycling than subjects who start at higher levels of physical activity (see Figure 3).

Modifiers of health benefits from cycling-related physical activity. Benefits from physical activity are the dominant health issue of cycling; however, several factors can modify these effects.

Physical activity recommendations suggest that activity should occur in bouts of at least 10 minutes (WHO, 2010). Although empirical evidence on threshold duration is limited, it can be assumed that extremely short bike rides will not contribute much to health, except insofar as they provide an active interruption to long periods of sedentary behavior (Sugiyama, Merom, Reeves, Leslie, & Owen, 2010).

To be health enhancing, activity should generally be of at least moderate intensity. There is no exact lower threshold and duration and intensity are usually aggregated linearly, although some research indicates that higher intensity cycling likely leads to even higher benefits (Schnohr, Marott, Jensen, & Jensen, 2012). There is consensus that regular cycling, such as on a daily or weekly basis, is more important for health than occasional vigorous exercise; however, the exact tradeoff between intensity and frequency remains poorly understood. Even activity frequencies of once per month have been associated with benefits. There are no noteworthy gender differences in how physical activity from cycling affects health, aside from breast cancer (Physical Activity Guidelines

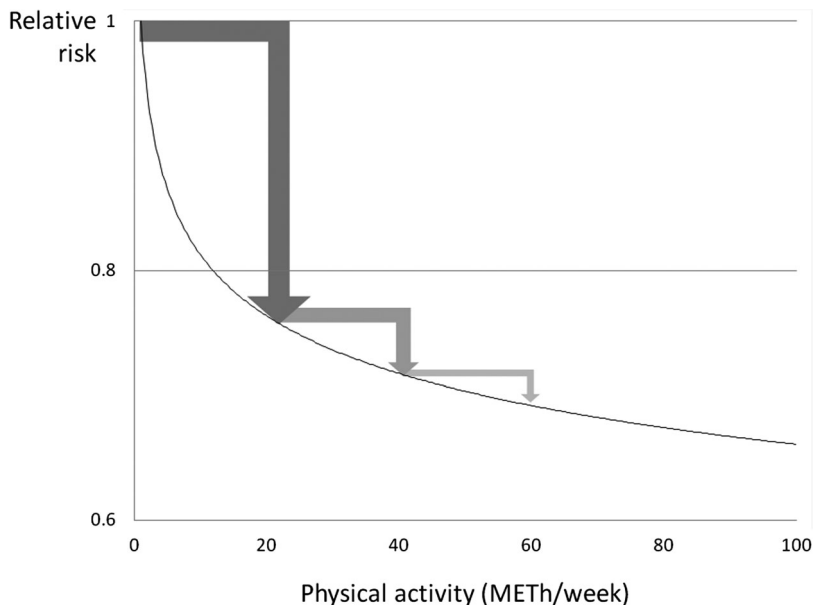


Figure 3. Illustration of the nonlinear dose–response relationship between physical activity and risk reduction (e.g. for mortality). Depending on the level of other physical activity, the same dose of cycling (horizontal segment of the arrows) will lead to considerably different risk reductions (vertical segments of the arrows).

Advisory Committee, 2008). Age may alter the effects of physical activity to some extent, although for mortality, evidence is mixed (Wen et al., 2011; Woodcock et al., 2011). In youth, benefits materialize in terms of cardiorespiratory endurance and muscular strength, whereas elderly people benefit in terms of functional health, reduced risk of falling, and improved cognitive function, in addition to benefits that occur in all age groups (i.e. reduction in mortality and various disease risks) (Physical Activity Guidelines Advisory Committee, 2008).

From a policy perspective, the most relevant modifier of health benefits from cycling is arguably ‘other physical activity’. The benefits resulting from cycling depend heavily on how active cyclists would be without cycling. If cycling succeeds as a travel mode appealing to those least inclined to exercise, its potential to contribute to public health is remarkable. Current research suggests that among cyclists, cycling is the predominant source of physical activity, and in high cycling countries, activity gaps, for example, between men and women are narrowed (Bassett, Pucher, Buehler, Thompson, & Crouter, 2008; Davison, Werder, & Lawson, 2008; Garrard, Handy, & Dill, 2012; Pucher & Buehler, 2007; Pucher, Buehler, Bassett, & Dannenberg, 2010; Smith et al., 2008; Voss & Sandercock, 2010; Wanner et al., 2012).

Crash Risk from Cycling

The topic of crash risks from cycling includes falls and collisions, risks of injuries (by severity), and risk of fatality (hereafter referred to as crash risk). The crash risk associated with cycling is one of the few disadvantages of this travel mode. Both decision-making on safety measures and cycling promotion, in general, require an understanding of crash risks that allows for sound comparisons. The main concepts addressed in this review are illustrated in the framework in Figure 4, that is, crash risk conceptualized as an exposure-adjusted rate (i.e. ratio between adverse events and an exposure measure), and impacts referring to the number of adverse events occurring in a specific population over a defined period of

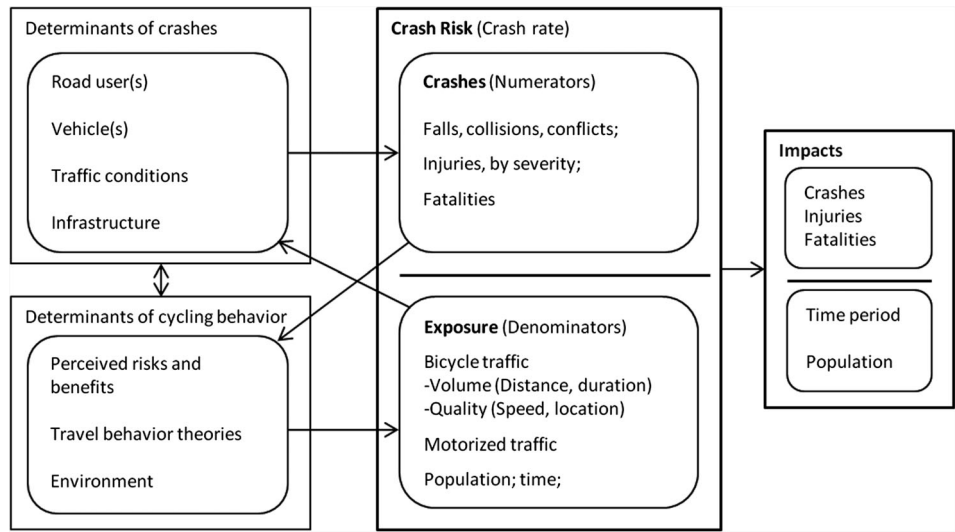


Figure 4. Conceptual framework of safety of cycling (adapted from Schepers et al., 2014).

time. Diagonal arrows indicate ‘feedback’ mechanisms, that is, ‘perceived safety’, and ‘safety in numbers’ (see below), which affect determinants of crash risk.

General overview of crash risks of cycling. There are a number of different statistics, types of data, or indicators that can be considered when describing safety of cycling. The public or individuals’ perception of safety of cycling seems predominantly influenced by absolute numbers of crashes, and in particular by the most severe crashes with fatalities reported by the media. For policy and planning decisions, such data are insufficient, since they cannot point to particular dangers (i.e. determinants of crashes) linked to specific behaviors, traffic conditions, types of infrastructure, or locations in a network (OECD & International Transport Forum, 2013). To address such issues, exposure-adjusted crash risks, or crash rates are required.

Crash rates can be based on different exposure measures (denominators), such as crashes per number of trips, crashes per distance, or crashes per time (among others). Which indicator(s) to use depends on the decision-making context. For example, cycling advocates often argue that a distance-based comparison is not ‘fair’, because cars travel much faster and hence cover longer distances. As a result, cycling fares much worse when crash rates are compared per distance, rather than per trip or per time. Choosing the right measure for such comparisons, however, is less an issue of ‘fairness’, rather than of understanding the nature of the available data and the comparison (i.e. the policy issue) at hand. Mindell, Leslie, and Wardlaw (2012) identify three categories of common mistakes when comparing crash rates:

- ‘Not selecting comparable numerators, that is, failing to include all transport casualties or to exclude non-transport casualties.’²
- ‘Choice of a misleading denominator, such as comparing cycling fatality rates using population size as the denominator (e.g. in international comparisons).’
- ‘Not accounting for different types of journeys undertaken in each mode, notably long-distance car travel (...).’

The reason for flawed comparisons using ill-suited safety indicators is often the sheer lack of (better suited) data. In contrast to epidemiological studies on physical activity and health, where both exposure and outcome are measured within the same individuals, routinely available data on crash rates of cycling usually consist of a combination of crash report data from official crash statistics (numerator) and, if available, exposure data from various other sources (denominator) (see Table 2). Each specific indicator has its own tradeoff between data availability and accuracy. For example, 0.2 in 100 000 people older than 65 years die cycling in the UK every year, while in the Netherlands this rate is 3.5/100 000 (International Traffic Safety Data and Analysis Group, 2014). However, such rates are of limited value to judge safety of cycling, because they do not reflect the fact that elderly people in the Netherlands cycle much more than those in the UK (see Figure 9).

Table 2 provides an overview of common safety indicators and a brief description of their advantages and disadvantages.

Clearly, crash rates become more meaningful when the denominators reflect the risk-relevant behavior, such as cycling (Martínez-Ruiz et al., 2014). The 2014 Benchmarking Report by the Alliance for Biking and Walking takes a fairly crude approach by presenting fatality rates per 10 000 bicycle commuters,

Table 2. Overview of indicators used to measure crashes (numerators) and corresponding exposures (denominators)

Indicator	Description	Pros/cons
<i>Numerators (Incidents)</i>		
Absolute number of crashes	Routinely available from police reports or hospital records	Basic, most common type of data; severe underreporting of minor crashes, in particular those without involvement of cars and/or others, and/or without injuries
By crash type	Various subcategories, including involved parties, crash location, etc.	Can help reduce mismatch in compared data; inconsistent definitions and recordings
With/without injuries	Crude separation of crashes with and without injured parties involved	Simple measure of relevance of crashes; underreporting is a problem for less severe crashes
By severity of injury	By degree of treatment required	Refined measure of relevance of crashes; inconsistent definitions and recordings
Fatalities		Reliable records, no underreporting; rare events, limited statistical inference
<i>Denominators (Exposures)</i>		
Population	Routinely available	Most basic way to adjust absolute number of crashes for different sizes of comparison areas; of limited value when levels of cycling differ
Number of trips	Can be derived from mode share, a common measure to describe travel patterns	Simple way to adjust for different levels of modes across comparison areas; variation in trip distances is not reflected
Distance traveled	Available from travel surveys	More accurate estimate of relevant exposure
Time traveled	Available from travel surveys	Require sufficient sample size (e.g. number of cyclists surveyed within comparison area)

which range anywhere between 0 and 40 cyclist deaths per 10 000 bike commuters in large US cities. However, these rates are unreliable due to both few fatalities and low numbers of bike commuters in many cities (Alliance for Biking and Walking, 2014).

Pucher and Buehler have published a number of international comparisons of cycling issues, including safety (Pucher & Buehler, 2006, 2007, 2008; Pucher & Dijkstra, 2003; Pucher et al., 2010). In Pucher and Buehler (2008, 2012), they present fatality and injury rates of cyclists per distance traveled for selected countries (see Figure 5). Such statistics provide a good sense for the magnitude of the issue. With approx. 5.5 cyclists killed per 100 million km cycled, deadly crashes are rare even in the USA. However, this rate is five times higher than that in the Netherlands or Denmark, indicating that there clearly is room for improvement.

Mindell et al. (2012) provide examples for both distance- and time-based crash rates which they compare by age, sex, travel mode, and type of incident. For example, in the UK the fatality rate for cycling (25 per billion kilometer) is about 10 times higher than for driving (2.3 per billion kilometer), although data issues may have inflated this contrast somewhat. At the same time, the average driving distance is approximately 100 times larger than for cycling. Per time

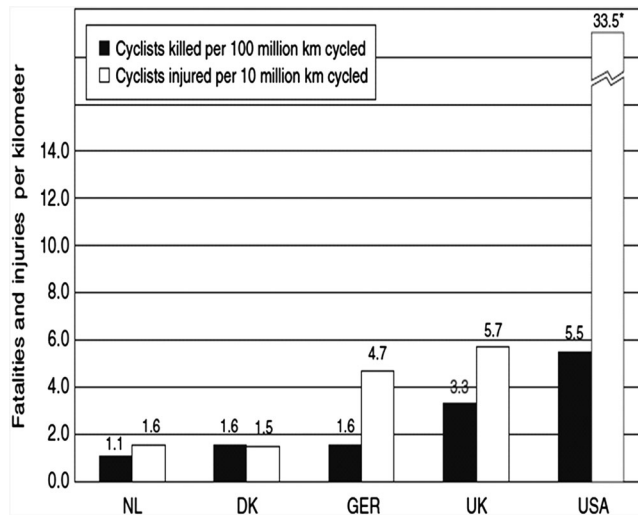


Figure 5. Cyclist fatality rates and nonfatal injury rates in the Netherlands, Denmark, Germany, UK, and the USA, 2004–2008. *The cyclist injury rate for the USA is off the chart and is thus shown with a discontinuous bar.

Source: First published by MIT Press in Pucher & Buehler (2012).

traveled, cycling is riskier than walking (see Figure 6), but per distance, cycling is safer.

Tin Tin, Woodward, and Ameratunga (2010) found approx. 15 times higher injury rates for cyclists (30 per million hours), compared with drivers in New Zealand, with a clear widening of the gap over the past couple decades. Some additional rates have been published by OECD (2013).

Specialized prospective studies measure exposure within the same subjects as the reported crashes (de Geus et al., 2012; Int Panis et al., 2011; Poulos et al., 2012) (www.pasta-project.eu). The SHAPES Study followed 1087 regular Belgian cyclists over one year, during which cyclists reported their cycling distance and

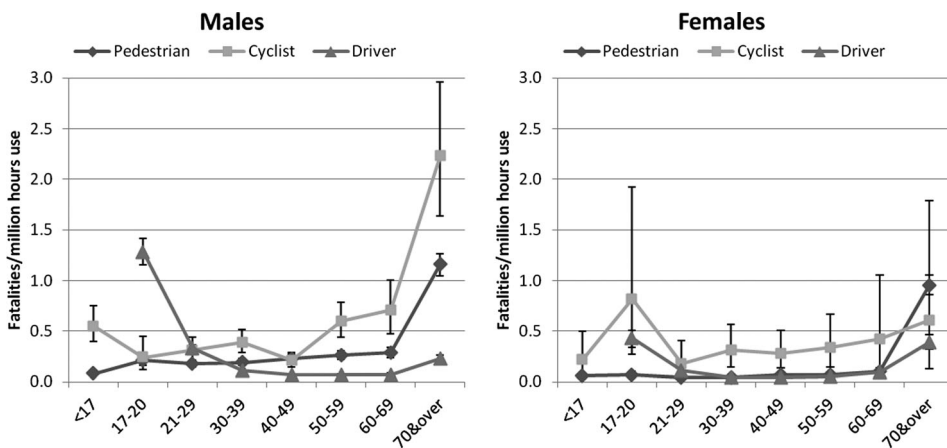


Figure 6. Fatality rates per million hours' use by travel mode, age, and sex in England, 2007–2009. Source: Mindell et al. (2012).

crashes on a weekly basis. The incidence rate for minor crashes was 4.7 per 100 000 km cycled (de Geus et al., 2012). In a similar study, Hoffman, Lambert, Peck, & Mayberry (2010) followed 962 cyclists in Portland, Oregon, over a period of one year and observed incidence rates of 9.3 per 100 000 km for all injuries and 2.4 for serious injuries.

In the so-called safety performance functions (AASHTO, 2010), both cycling and motorized traffic can be considered (Elvik, 2009), but to date, this is not being done routinely for cycling (Nordback, Marshall, & Janson, 2014).

Due to the increased complexity of interactions between vehicles, intersections increase the risk for bicycle crashes, compared to linear road segments or trails. By how much, however, is difficult to quantify, because studies on safety risks treat intersections and road segments as separate entities (Moore, Schneider, Savolainen, & Farzaneh, 2011; Nordback et al., 2014; Reynolds, Harris, Teschke, Crompton, & Winters, 2009).

Other specialized study designs can provide further insights into the safety of cycling. Teschke et al. provide a rare study on crash risks in relation to different types of route infrastructure (2012). In their study of cycling injuries requiring hospitalization in Vancouver and Toronto, Canada, the probability for a crash was almost ten times lower on a cycle track (i.e. a ‘protected bike lane’, physically separated from traffic), compared to major streets with parked cars (see Figure 7). Lusk et al. (2011) observed approximately 30% lower crash risks on cycle tracks, compared to comparable roads without cycle tracks. In an earlier analysis of Toronto cyclists, Aultman-Hall and Kaltenecker (1999) observed higher collision rates on roads, compared with off-road paths and sidewalks.

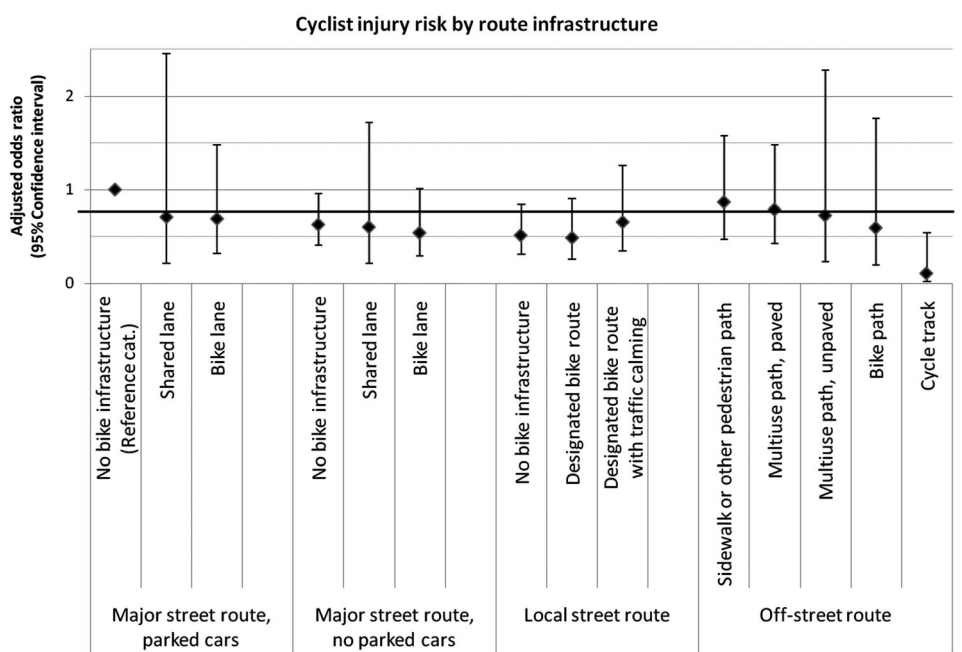


Figure 7. Cyclist injury risk by route infrastructure, relative to ‘Major streets with parked cars and no bike infrastructure’. For example, bicycle crashes are only half as likely on local streets (Odds ratio=0.5, Odds ratio is a measure of relative risk). Based on data from Teschke et al. (2012.)

and injuries, the rates were lowest on roads. Overall, rates per kilometer for all incidents were 26–68 times higher than for driving.

In a review of earlier studies on infrastructure and cycling safety, Reynolds et al. (2009) concluded that there was a principal trend “that clearly-marked, bike-specific facilities (i.e. cycle tracks at roundabouts, bike routes, bike lanes, and bike paths) were consistently shown to provide improved safety for cyclists compared to on-road cycling with traffic or off-road with pedestrians and other users” (p. 15).

Another related issue is perceived safety, which may or may not be correlated with objective safety (Elvik & Bjørnskau, 2005). More importantly, perceived safety is a crucial determinant of cycling behavior (Carver et al., 2005; Fishman, Washington, & Haworth, 2012; Heinen, Maat, & van Wee, 2011; Hoehner, Brennan Ramirez, Elliott, Handy, & Brownson, 2005; Jacobsen, Racioppi, & Rutter, 2009; Kerr et al., 2006; Morckel & Terzano, 2014; Nelson & Woods, 2010; Noland, 1995; Ogilvie, Egan, Hamilton, & Petticrew, 2004; Reynolds et al., 2009; Sanders, 2015; Van Dyck et al., 2012; Winters & Teschke, 2010). As such, addressing the issue of perceived safety is primarily an effort to promote cycling. In most cases, increasing objective safety is certainly a necessary part to improving perceived safety, but it may not necessarily be sufficient. Other factors which may be equally important in influencing perceived safety of cycling may include positive experiences through formal and informal learning and training options, or on facilities protected from motorized traffic, such as trails and traffic-calmed zones (Pucher & Buehler, 2008). In addition, a general sense of public acceptance, support, or even enthusiasm for cycling, among other factors, will increase the perception of cycling as a safe travel mode.

Modeling safety impacts of cycling. Impact modeling of cycling safety aims to estimate injuries and fatalities, which are attributable to a certain level of or change in cycling (i.e. increases in cycling) in a defined population, either as part of an evaluation of a measure or policy (Rojas-Rueda, de Nazelle, Tainio, & Nieuwenhuijsen, 2011; Woodcock et al., 2014), or, more often, as part of hypothetical scenario (what if?) calculations (Creutzig, Mühlhoff, & Römer, 2012; Edwards & Mason, 2014; de Hartog et al., 2010; Holm, Glümer, & Diderichsen, 2012; Jarrett et al., 2012; Lindsay, Macmillan, & Woodward, 2011; Macmillan et al., 2014; Rabl & De Nazelle, 2012; Rojas-Rueda et al., 2013; Stipdonk & Reurings, 2012; Woodcock et al., 2009).

For example, Schepers and Heinen (2013) found that in the Netherlands, a hypothetical mode shift from short car trips to cycling would not result in higher numbers of fatalities; however, the number of cyclists seriously injured would increase mainly due to crashes without motor vehicle involvement. Macmillan et al. (2014) simulated long-term impacts of planning scenarios in New Zealand. By 2051, increases in cycling would lead to an additional 85–250 fatalities from crashes, but physical activity-related reduction in all-cause mortality would avoid between 650 and 4000 premature deaths. Rabl and de Nazelle (2012) quantified costs associated with fatal bike crashes and other factors from shifting a 10 km commute from car to bike. Average cost from fatal crashes added up to €50 per person and year, compared with savings of €1300 from physical activity-related benefits.

In contrast to the effects of physical activity, crash risk is not a generalizable physiological phenomenon, with the exception of elderly subjects being at

higher risk for severe injuries. Crash risks vary dramatically across time, space, and individuals. For example, a certain route may be perfectly safe to ride for a skilled rider, in daylight, or during off-peak hours. The crash risk may, however, be dramatically different for a less experienced rider, at night, or during rush-hour (Woodcock et al., 2014).

Impact models, therefore, require accurate crash risks closely matched to the population, measure or policy, and area or location of interest. This can be particularly for small-scale projects, such as infrastructure improvements, because, as described above, crash rates are usually only available from large-scale data sets, such as national or regional surveys and crash statistics.

Further, crash rates may often be affected by the same measure that is being assessed. For example, a city may intend to increase cycling by building a network of separated bicycle facilities (e.g. cycle tracks Thomas & DeRobertis, 2013) or traffic-calmed routes (e.g. bicycle boulevards Dill, 2009), which would decrease crash risks. However, empirical evidence to quantify such effects is extremely limited (Teschke et al., 2012).

Also, changes in cycling are often not attributable to specific projects (e.g. infrastructure types), but are rather the result of broader schemes or policies. Safety impact models therefore sometimes apply nonlinear crash risk functions, which reflect that with increasing levels of cycling (through whatever measures), crash rates increase less than cycling levels (Schepers & Heinen, 2013; Woodcock et al., 2013), a phenomenon referred to as ‘safety in numbers’ (Elvik, 2009; Jacobsen, 2003). While this relationship has been observed widely (Blaizot, Papon, Haddak, & Amoros, 2013; Elvik, 2009; Götschi, 2011; Jacobsen, 2003; OECD & International Transport Forum, 2013; Robinson, 2005), its interpretation has been criticized for being too focused on one of the two possible causal directions — the higher number of cyclists improving safety — while equally, more safety increasing the numbers of cyclists (‘numbers in safety’) would, and likely has, lead to the same nonlinear relationship (Bhatia & Wier, 2011). Pathways in both directions are plausible, but there is no research available that could quantify the pathway-specific contributions to safety or numbers, respectively. It should be noted that the direction of causality does not affect impact calculations. Caution should, however, be exercised when drawing policy conclusions based on the correlation of levels and safety of cycling. Figure 8 illustrates likely pathways.

It has been suggested that not only other cyclists, but also all road users benefit from increased safety linked to higher levels of cycling, for example, because of lower traffic speeds (Marshall & Garrick, 2011; Wegman, Zhang, & Dijkstra, 2012). For impact modeling this might imply that indirect effects on non-cyclists should be considered; however, to date this has only been addressed by a few studies (de Hartog et al., 2010; Schepers & Heinen, 2013).

In conclusion, impact modeling of crash risks is a highly case-specific affair and findings are hard to generalize or compare across studies. Compared with modeling physical activity impacts, identifying sound crash rates is the main challenge. Also, estimating potential changes in crash rates resulting from or occurring in parallel with the change in cycling of interest requires assumptions which introduce substantial uncertainty. Nonetheless, some patterns seem to hold true throughout studies conducted to date, namely that increases in cycling lead to disproportionately smaller increases in crashes, and that negative impacts of crashes do not outweigh benefits from physical activity.

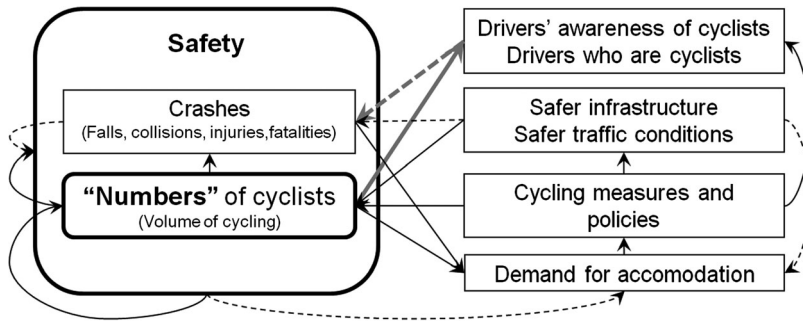


Figure 8. Schematic illustration of relationships between ‘safety’ and ‘numbers’, and selected intermediate factors. The verbatim interpretation of ‘safety in numbers’ is indicated with bold grey arrows. Selected additional pathways are indicated with black arrows. Solid arrows reflect positive associations (read ‘increases’), and dashed arrows reflect negative associations (read ‘decreases’).

Selected additional issues related to cycling crash risks. Several modifiers of crash risks, such as the level of cycling (‘safety in numbers’) or types of infrastructure, as well as the role of perceived safety as a determinant of cycling behavior, have been mentioned in the above sections. In the following, selected additional topics related to cycling safety are addressed. For helpful overviews of further factors related to cycling safety, see Wegman et al. (2012), Schepers, Hagenzieker, Methorst, Van Wee, and Wegman (2014), Ragland, Grembek, Orrick, and Felschundneff (2013), and the OECD report ‘Cycling, Health and Safety’ (2013).

Traffic conditions, in particular volume and speed, are certainly important for cycling safety, but empirical evidence is rare (Elvik, 2009; Strauss, Miranda-Moreno, & Morency, 2013, 2014). Speed of vehicles involved in a collision is clearly related to injury severity (AASHTO, 2010), but severe injuries may be less frequent on roads with higher traffic volumes (Klop & Khattak, 1999). Nordback et al. (2014) found that in Boulder, CO, higher traffic volumes of both motorized vehicles and bicycles reduce cyclist crash rates (i.e. less than linear increase in crashes) at intersections. Bunn et al. (2003) found that traffic calming schemes reduce fatal crashes by a third and crashes with injuries by about 10%. Although the majority of crash victims in this meta-analysis were pedestrians, the safety improvements for cyclists may be similar (Wegman et al., 2012). Volume and

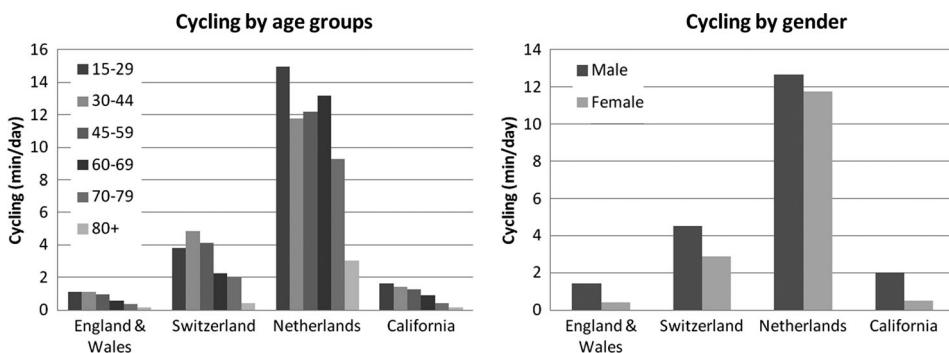


Figure 9. Distribution of cycling across age groups and gender in an international comparison. Countries such as the Netherlands, with high levels of cycling and safe cycling conditions, manage to attract people of both genders and across all age groups to cycling (Götschi et al., 2015).

speed of motorized traffic should be regarded as key criteria for the choice of bicycle infrastructure measures. Higher volumes and speeds call for higher degrees of physical separation of cyclists and motorized traffic, and vice versa, mixed traffic is more adequate with lower volumes and slower speeds (Land Transport Safety Authority, 2004; Wegman et al., 2012). The same logic applies to mixed traffic of cyclists and pedestrians, but few studies have looked at conflicts between the two (Haworth & Schramm, 2011; Shaw, Poulos, Hatfield, & Rissel, 2014).

Large vehicles, such as trucks, pose particular risks to cyclists due to their extended blind spots, which can cause dangerous conflicts in turning movements (Morgan, Dale, Lee, & Edwards, 2010).

A controversially debated topic is bicycle helmets (Robinson, 2007). It is undisputed that helmets reduce the risk of severe head injuries in a bike crash by about 50% (Elvik, 2013). Cycling advocates, however, point out that helmet wearing rates are lowest in countries where cycling is safest, for example, the Netherlands. Some countries have or debate mandatory helmet wearing laws, which are criticized for putting an (additional) burden on cyclists (Robinson, 2003). Overall, evidence on helmet laws is insufficient to weigh desired injury prevention effects against unintended effects of less people cycling (De Jong, 2012; Fyhri, Bjørnskau, & Backer-Grøndahl, 2012; Grant & Rutner, 2004; Robinson, 2006).

Exposure to Air Pollution

Epidemiologic evidence on cycling-related exposure to air pollution. Exposure to air pollution has been associated with premature mortality and health conditions including cardiovascular disease, lung cancer, exacerbation of asthma, acute respiratory infections in children, chronic bronchitis in adults, decreased lung function, low birth weight, and preterm birth (Brunekreef & Holgate, 2002; Kim, Kabir, & Kabir, 2015).

Motor vehicles are a major source of air pollution, and commuting represents a high-exposure period for people living in urban areas (Karanasiou, Viana, Querol, Moreno, & de Leeuw, 2014). Motor vehicles emit a variety of air pollutants including fine particles, nitrogen dioxide, ozone, and volatile organic compounds, which is of interest because these may be more toxic than background pollution (de Hartog et al., 2010; Krzyzanowski, Kuna-Dibbert, & Schneider, 2005; Panel on the Health Effects of Traffic-Related Air Pollution, 2010; Schlesinger, Kunzli, Hidy, Götschi, & Jerrett, 2006). Commuting in traffic has been shown to contribute up to 30% of inhaled daily dose of black carbon, and about 12% of daily exposure to PM_{2.5} (particles $\leq 2.5 \mu\text{m}$ median diameter), despite individuals traveling for only about 6–8% of the day (Karanasiou et al., 2014).

Cycling can result in greater exposure to air pollution because, first, air pollution concentrations are higher in traffic than most other places we spend time (Kaur, Nieuwenhuijsen, & Colville, 2007), and second, increased ventilation rates lead to higher volumes of inhaled air (Int Panis et al., 2010; Zuurbier, Hoek, van den Hazel, & Brunekreef, 2009). Bigazzi and Figliozzi (2014) as well as Karanasiou et al. (2014) provide helpful reviews. Air pollution concentrations in cycling environments depend on background pollution; proximity, volume, vehicle mix, and flow of traffic; weather and wind conditions; and micro-scale topography such as street canyons (Panel on the Health Effects of Traffic-Related Air Pollution, 2010). Inhalation rates depend on the intensity of cycling (i.e. speed, slope, and

weight). Further, compared to car drivers, cyclists lack a protective shell around them, although some studies indicate that air pollution concentrations can be higher inside vehicles than outside (Dons, Int Panis, Van Poppel, Theunis, & Wets, 2012).

A number of studies have looked at how cycling affects exposure to air pollution (Bernmark, Wiktorin, Svartengren, Lewné, & Åberg, 2006; Briggs, de Hoogh, Morris, & Gulliver, 2008; Chertok, Voukelatos, Sheppard, & Rissel, 2004; de Nazelle et al., 2012; Gulliver & Briggs, 2004; Int Panis et al., 2010; Rank, Folke, & Homann Jespersen, 2001; Zuurbier et al., 2010). These studies estimate exposure to PM_{2.5} while cycling to be about double the background pollution, and about 20% lower than while driving, although local circumstances are influential and ratios can vary considerably for different pollutants (Karanasiou et al., 2014). Increased ventilation rates during cycling are estimated to increase inhaled dose of pollutants by up to a factor five, compared to sleeping and resting (de Nazelle, Rodríguez, & Crawford-Brown, 2009; Johnson & Georgopoulos, 2002; Karanasiou et al., 2014).

Direct evidence on air pollution-related health effects of cycling is scarce, given the enormous challenges of investigating this question. Only few studies found associations between cycling-related exposure to air pollution and short-term effects on health (e.g. asthma attacks) or biomarkers in cyclists (Bos et al., 2011; Strak et al., 2010). There are no studies available that link cycling-related exposure to air pollution directly to long-term health effects, which leaves various questions open about whether and how short peak exposures during cycling translate into clinically and public health-relevant chronic diseases.

Health impacts of exposure to air pollution. Health impact modeling of cycling-related air pollution exposure faces two main challenges:

- Accurately estimating air pollution exposure of cyclists studied. (And if assessing the impacts of replacing car trips, also exposures of drivers and the population in general.)
- Associating exposures while cycling with health endpoints of interest, given the lack of empirical epidemiological evidence, which could provide ready-to-use relative risk estimates.

Air pollution levels depend on a number of factors, such as regional and local emission sources, weather conditions, and topography, and are highly variable spatially and over time. Exposure of cyclists further depends on the location of a cycling route relative to major roadways, or the position of a cyclist relative to cars on a roadway, and traffic conditions such as volume and flow, vehicle mix, and fuel type. Cyclists' exposures to air pollutants generally decrease exponentially with increased distance from motorized traffic (Zhu, Hinds, Kim, & Sioutas, 2002). In the absence of local air pollution measurements or spatial air pollution models, impact models for cycling are required to make assumptions on average ratios between in traffic and background exposure, and apply these to routinely available air pollution data.

In contrast to air pollution levels, ventilation rates are fairly predictable and depend directly on the intensity of physical activity. However, poor data on the intensity (or speed) of cycling can introduce great uncertainty into air pollution

impact modeling, because ventilation rates vary substantially between leisurely and brisk cycling speeds.

Once the inhaled dose of air pollution while cycling is assessed, it needs to be related to epidemiologic effect estimates. Since estimates for long-term health outcomes, which are of greatest public health interest, are usually based on long-term cumulative exposure to all sorts of air pollutants, impact models need to assess to what extent cycling increases this total exposure to (background) air pollution.

For example, de Hartog et al. (2010) estimated impacts of shifting 500 000 short car trips to cycling, applying relative risk estimates from two long-term studies (Beelen et al., 2008; Pope III et al., 2002). Compared to driving, cycling increased the mortality risk due to air pollution by 0.5–5%, depending on the pollutant. People living near busy roads could experience reductions in mortality risks of similar magnitude due to reduced air pollution from shifts to cycling. Cyclists would lose between 0.8 and 40 days in life expectancy due to increased exposure to air pollution compared to 3–14 months gained from physical activity. Several impact model studies applied similar approaches to estimate cycling-related air pollution impacts and came to comparable conclusions, consistently showing harmful impacts of air pollution being small compared with benefits from physical activity (Grabow et al., 2011; Holm et al., 2012; Lindsay et al., 2011; Rabl & De Nazelle, 2012; Rojas-Rueda et al., 2011; Rojas-Rueda, de Nazelle, Teixido, & Nieuwenhuijsen, 2012; Woodcock et al., 2009).

Modifiers of cycling-related exposure to air pollution. While air pollution-related risks of cycling may be of a smaller magnitude than benefits from physical activity, it is nonetheless desirable to minimize exposures as much as possible. Cyclists can basically only do so by choosing less polluted routes or avoiding rush hour traffic, both of which may not be feasible, especially for commuters (Hertel, Hvidberg, Ketzel, Storm, & Stausgaard, 2008). Planners could facilitate this by considering air pollution levels among other criteria, when deciding between alternative route options when planning bike route networks. Ideally, bicycle networks provide users with options to choose between direct, but more polluted routes and somewhat longer off-road alternatives, such as trails or bike paths entirely separated from motorized traffic. Along roads with cars, bicycle facilities physically separated from traffic, that is, protected bicycle lanes, may provide some reduction in exposure to exhaust fumes (McNabola, Broderick, & Gill, 2009). Reducing overall travel demand through smart land-use policies; shifting trips to alternative modes, including cycling; lowering traffic speeds; and supporting low emission technologies ultimately provide the most sustainable approaches to avoid risks from air pollution not only for cyclists, but also the entire population.

Other health pathways. Numerous other health outcomes or pathways that have been linked to cycling are beyond the scope of this review. For a helpful overview, see Garrard, Rissel et al. (2012). These include weight control, fitness, mental health and emotional well-being, cognitive functioning, health inequality, exposure to noise (James, Ito, Buonocore, Levy, & Arcaya, 2014; Rabl & De Nazelle, 2012), livability,³ community cohesion and social connectedness, reduction in crime, health improvements due to greater mobility from cycling — resulting in improved access to health care (James et al., 2014), and cycling for therapy and rehabilitation of patients, among others.

Discussion and Conclusions

Physical activity benefits are the dominant aspect of cycling from a public health perspective. Safety risks cause a smaller, negative impact on public health, but play a greater role for the individual, as they affect crash victims immediately and deter potential cyclists from riding. Air pollution impacts are small, compared to physical activity benefits.

While the exact magnitude and balance of benefits and risks of cycling will depend on local conditions, based on the existing evidence, planners, health professionals, and decision-makers alike can be confident that promoting cycling is well worth pursuing from a health perspective alone, even without accounting for various additional benefits (Litman, 2012). Many approaches to promote cycling also align well with efforts to reduce risks. The evidence suggests that reducing motorized traffic volumes and speeds, and separating cyclists from traffic through infrastructure or bike routes on less frequented roads play key roles in attracting more people to cycling — as well as in increasing safety. It is also important to recognize that estimates of the benefits and risks of cycling are based on current levels of physical activity and current cycling conditions. If trends toward physical inactivity continue, and at the same time cycling is made safer, the benefit–risk ratio will improve further.

A key reason to pursue day-to-day cycling as a strategy to improve public health is its feasibility for large parts of the population and, in particular, all age groups. Cycling offers great potential to keep elderly people active and mobile if conditions are safe, as data from the Netherlands demonstrate (see Figure 9). Cycling that is perceived as a safe and convenient transport option is more likely to appeal to insufficiently active individuals than activities without co-benefits. Reaching these people must be a priority in physical activity promotion because health benefits are most pronounced in the least active individuals. As such, cycling offers potential to overcome inequity issues of sports and leisure time physical activities, which are more popular in high-income, well-educated, and often more health-conscious segments of the population (Bell & Cohen, 2009).

To what extent health benefits serve as a motivator for day-to-day cycling is not well understood, but research indicates that especially utilitarian cyclists (e.g. commuters) may under-value this aspect (Götschi & Hintermann, 2014), which would present an opportunity for information campaigns on (the magnitude of) health benefits of cycling. The promise of health benefits, however, is unlikely to sway potential cyclists who currently perceive safety risks as too high a barrier; therefore, safety belongs in the focus of all bicycle promotion efforts.

Two recent developments in bicycle promotion are worthwhile mentioning. The rapid rise of electric-assist bicycles (e-bikes) in some countries has raised questions with regard to its impacts for health and safety. E-bikes' great promise to public health is that users may choose to ride more often, for longer distances, in steeper terrain, with higher loads, or at an older age. As such, e-bikes have the potential to expand cycling to parts of the population for which conventional cycling is not practical.

Bike sharing systems have led to a renaissance of urban cycling in many cities (<http://bike-sharing.blogspot.com>) (Fishman, Washington, & Haworth, 2013). When assessing the health impacts of bike sharing schemes, the same factors apply as to conventional cycling. However, usage may be less regular, and crash risks may differ due to less experienced or more prudent users, among other factors.

A number of research issues require further attention. Given the robust evidence of benefits from physical activity, research into safety issues of cycling and effectiveness of measures to promote cycling is most pressing. Emerging data collection technologies, such as route-tracking apps or refined survey designs, as well as progress toward bicycle traffic models (Kuzmyak, Walters, Bradley, & Kockelman, 2014), promise substantial contributions in the near future. Improvements in impact modeling will depend equally on refined approaches of how to generalize safety (and air pollution) factors, as well as on improved input data on changes in cycling from implemented measures and policies. To integrate health into the routine planning context, publicly available tools, such as HEAT (www.euro.who.int/HEAT) or ITHIM (www.cedar.iph.cam.ac.uk/research/modelling/ithim/), provide a promising approach. Efforts to expand and improve these and similar models are ongoing. The success of integrating such tools into standard planning guidance will depend on whether complexity and user friendliness can be kept in balance.

In conclusion, health impacts of cycling should play a central role in considerations about bicycle promotion. Benefits from physical activity are of such magnitude that they are worth pursuing by individuals equally as by society, even though locally, safety issues may need to be addressed simultaneously. In many aspects, health benefits of cycling are more tangible than other reasons to promote cycling and provide a quantifiable case for investments in this mode of transport.

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Notes

1. The dose of cycling was quantified in terms of metabolic equivalents of task (MET) times the cycling duration per week (MET.hours per week). MET is a measure of intensity of physical activity, where one unit is the equivalent of the metabolic rate (energy consumption) at rest.
2. For example, bicycle crashes among playing children, in mountain biking or in road racing.
3. Livability is a term coined by the US transport administration to refer to a range of community qualities which are often less tangible than traditional transport performance measures, that is, access to jobs, affordable housing, quality schools, and safe streets (www.fhwa.dot.gov/livability).

ORCID

Thomas Götschi  <http://orcid.org/0000-0002-1202-7863>

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