1. Cycling, safety, health and policy – necessary linkages, suggested approaches

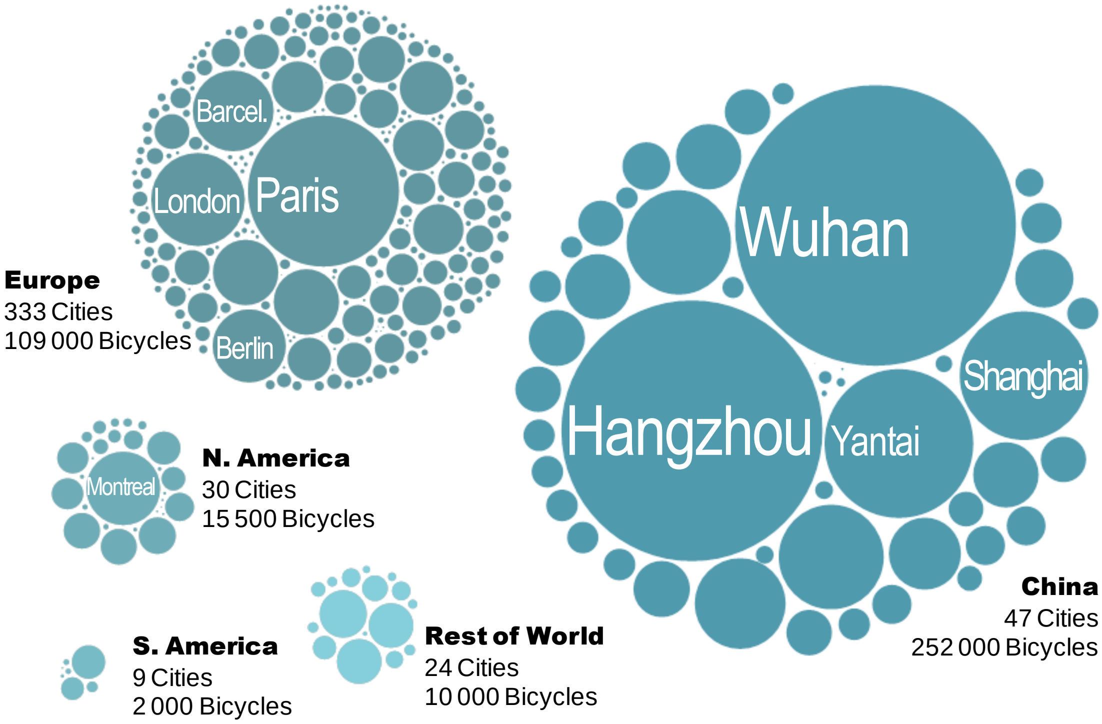
Many countries are promoting cycling as a way to improve health and quality of life while reducing the negative impacts of transport in terms of congestion and pollution. Safety, however, is a key concern since cyclists are relatively unprotected road users. This chapter addresses the key issues relating to cycling safety and links them to a greater discussion of health, safety and cycling. The deleterious impact of crashes on cyclists' health is only one part of the health impacts of cycling – and it is often overvalued in policy discussions. This chapter examines the full range of health impacts and discusses critical elements necessary for cycling policy evaluation. It also suggests a way forward for framing cycling and road safety policy such that health benefits are maximised.

1.1. Pro-cycling Policies and Safety

Bicycles are an essential part of the urban mobility mix. They use no fossil energy, deliver important health benefits, and can improve the liveability of cities. The attraction of the bicycle resides in its ability to provide an affordable and seamless door-to-door mobility option. Cycling is as versatile as walking but can cover greater distances at higher speeds. It represents an alternative to cars and allows for greater freedom of movement than scheduled public transport services. When combined with the latter, bicycles can also extend the range and attractiveness of public transport. Bicycles may decrease pollution and congestion if they successfully replace automobile traffic[1]. Bicycles are well suited to respond to the great number of short to medium distance trips that are typical of urban travel. While powered two-wheelers offer similar advantages, they also impose greater societal costs linked to crash frequency and outcomes as well as air pollution.

That many cities are introducing advanced public bike systems is a clear indication that bicycling is becoming a central part of the mobility solution in many urban settings (see Figure 1.1). Beyond public bike sharing systems, there are a number of pro-cycling policies and frameworks that are being implemented throughout International Transport Forum member countries[2]. Crucially, however, while there are many reasons to promote cycling, safety *per se* is not foremost among them in most countries. In fact, the *improvement* of cyclists' safety is a central element of many pro-cycling policies since evidence points to vulnerability of cyclists in road traffic.

Figure 1.1 **Example of pro-cycling policies: Public Bicycle sharing systems worldwide in 2012**



Source: ITF, data from Data from MetroBike, LLC (http://www.MetroBike.net, accessed 12 December, 2012)

How dangerous is cycling compared to other modes? Statistics (see Table 1) and studies detailing the comparative risk of injury or death for cyclists versus car occupants find significantly higher risks per unit of exposure for cyclists: e.g. 7.5 times higher injury risk and 6 times more fatality risk per kilometre in Norway (Elvik, 2009) (Vegdirektoratet, et al 2009), 6 times higher fatality risk per kilometre for the Netherlands (IRTAD, 2011)(SWOV, 2011), 15 times more injury/fatality risk per hour of travel in New Zealand (Tin Tin, Woodward and Ameratunga 2010). In a meta-analysis of data from Denmark, Great Britain, The Netherlands, Norway and Sweden (Elvik, Høye, et al. 2009) find that cyclists face 9.4 times the risk of being injured per kilometre as car occupants. Part of this disproportionate risk may stem from a bias in the data; an important share of car travel is comprised of relatively “safe” motorway kilometres. One Dutch study compared risks of fatal crashes for motorists and cyclists (including the risk to other traffic participants) *excluding* relatively “safe” motorway travel and found relatively similar mortality rates for cyclists and car occupants (21.0 and 20.8 deaths per million kilometres travelled respectively)(Dekoster and Schollaert 1999). Another Belgian study found that the relative risk of getting killed while cycling versus car travel dropped by 20%[3] if controlling for motorway travel(Hubert and Toint 2002). Whether these finding hold for other countries or regions is unclear and requires further study.

An additional element to consider when assessing the relative safety of cycling versus other modes is the selection of the exposure variable. We discuss issues related to lack of availability of exposure data further on but note here that the type of exposure variable selected (risk per trip, per distance or per duration) is not without consequence. For instance, the United Kingdom’s 2007 Road Casualties Annual Report found that cyclists faced 13 times more fatalities than car occupants per 100 million kilometres of travel but only 4 times more fatalities per 100 million hours of travel or trips (Department for Transport 2008).

It is not clear that changing the exposure variable results in a consistently different relative risk level – for instance, (Martensen and Nuyttens 2009) finds that fatality risk per minute travelled is essentially the same for cyclists and motorists in Belgium whereas this is not the case for New Zealand (Tin Tin, Woodward and Ameratunga 2010) (though the latter looks at both serious injury and fatality risk).

Table 1.1 **Relative risk for cyclists vs. other modes, selected countries (index, car driver=1)**

Below are indicators of relative risk of death and/or serious injury for a selection of countries reporting safety and kilometre-, trip- or duration-based exposure statistics for cyclists. Note that because of differences in reporting methodologies and coverage, especially for non-fatal injuries, the figures below should not be used to compare relative risk between countries, but rather to evaluate relative risk between modes within one country.

	Cycling	Walking	Moped	Motorcycle	Car (driver)	Car (pass.)
Netherlands[a] : *Annual number of **killed** per billion **kilometres** of travel, 2007-2009*						
	5.9	9.1	30.0	30.0	1.0	
Switzerland[b]: *Annual number of **killed** per billion **kilometres** of travel, 2010*						
	11.2	9.1		18.0	1.0	
Norway[f] : *Annual number of **killed** per billion **kilometres** of travel, 1998-2002*						
	5.9	8.4		10.2	1.0	
United Kingdom[g] : *Annual number of **killed** per billion **kilometres** of travel, 2008-2011*						
	14.4	16.9		51.3	1.0	
Denmark[a] : *Annual number of **casualties (killed and injured)** per billion **kilometres** of travel, 2010*						
	10.6	10.2	148.9	44.1	1.0	
United States[c] : *Annual number of **killed** per billion **trips**, 1999-2003*						
	2.3	1.5		58.3	1.0	
Belgium[d] : *Annual number of **killed** per billion **minutes** spent travelling, 2005*						
	1.2	0.8	12.9		1.0	
New Zealand[e] : *Annual number of injuries resulting in **death or hospitalisation** per million **hours** spent travelling, 2003-2007*						
	14.6	1.1	..	51.2	1.0	1.4

Sources:
a. (IRTAD 2011),
b. Swiss Federal Statistics Office (www.bfms.admin.ch), accessed October 15, 2012
c. (Beck, Dellinger and O'Neil 2007),
d. (Martensen and Nuyttens 2009),
e. (Tin Tin, Woodward and Ameratunga 2010),
f. (Vegdirektoratet, et al 2009),
g. UKDFT Road Safety Annual Report – Table RAS53001.

Box 1.1 **Crash Risk Factors and Cycling**

Participating in traffic is an inherently dangerous activity given the combination of multiple direct and indirect risk factors. Though much has been accomplished to reduce these risk factors or to reduce the likelihood of these risks resulting in injury crashes, they still persist. Below, we outline principal crash risk factors and discuss their relevance for cycling.

Fundamental Risk Factors

Speed: Evidence indicates that speed (absolute speed and relative speed differences among traffic participants) is positively correlated to an exponential increase in crash risk. Speed is also correlated to crash severity as it is an important component of kinetic energy which, in crashes involving bicycles, is directly released onto unprotected soft body tissue and skeletal systems.

Mass and Protection: Mass is the other component of kinetic energy. At constant speed, the larger the mass, the greater the amount of kinetic energy released. For cyclist crashes with heavier opponents (motor vehicles) the mass differential can be extreme thus contributing to increased severity of crash outcomes for cyclists. Protection can help absorb some of the crash-released kinetic energy but motor vehicles offer very much greater levels of protective engineering than cycling equipment (typically limited only to helmets, if worn).

Contributory Factors from Road Users

Lack of experience: For cycling, there is a difference between knowing *how* to cycle and knowing how to cycle *in a road environment*. Both may be addressed by early education but in cases of late adoption of cycling, special training might be desirable for adult cyclists since experience from motor vehicle driving may not be directly transferable to cycling. In addition, late adoptees of cycling may require fundamental training on the use of a bicycle.

Impaired use (Drugs and Alcohol): Use of drugs or alcohol, or both, significantly increases risk for road users. Single bike crash severity for cyclists may be lower than single motor vehicle crash severity (largely due to speed and mass differences) but risk-taking by impaired cyclists could expose them to greater involvement in motor vehicle-bicycle crashes (with largely detrimental outcomes for the cyclist). It may be that impaired people opt to use a bicycle rather than a motor vehicle in order to reduce their crash risk and in some jurisdictions, cyclists face lower blood alcohol limits than motorists (e.g. in Germany, the blood alcohol limit for car use is set at 0.05%, whereas for cycling it is 0.16%) (Juhra, et al., 2011). This is a practice worth re-assessing using available evidence on alcohol use and bicycle injury crashes.

Illnesses or Ailments: Visual or auditory impairment can be a contributing factor in bicycle crashes. The latter especially may be a factor in crashes resulting from overtaking. Wearing headphones may mimic this risk.

Emotion and Aggression: Anecdotally, crash risk exacerbation from aggressive behavior in traffic seems to be mainly attributable to motorists. This is not to say that aggressive behavior on the part of cyclists does not contribute to crashes – especially when it is combined with risk-taking behavior vis-à-vis other cyclists and pedestrians.

Fatigue and Distraction: Fatigue increases the risk of crash involvement. Cyclists may be even more prone to fatigue since cycling requires energy expenditure further complicating an already fatigued state. On the other hand, fatigued people may avoid cycling altogether or may find themselves becoming less tired as they cycle because of the beneficial impact of physical activity. Distraction may also be a contributing factor to crash risk for cyclists – especially for those using mobile phones or other electronic devices. The latter is an area where more research can help guide safety policy, especially as use of mobile ICT devices is increasing (Scheppers 2007).

Source: Adapted from (Wegman and Aarts 2006)

The majority of trips are made in view of travelling from point to point, not for travelling during a set amount of time. Because of this *distance-based* exposure variables have (when available) typically been seen as a superior measure of relative risk for *equivalent* trips. In reality, trips by bicycle and by car are not necessarily equivalent and travellers may adjust mode choice according to a wide range of factors (availability of parking, exposure to congestion, amenities at the destination, ease of linking with other modes, etc). For instance, although average trip lengths are greater for cars than for bicycles in Belgium, average per-trip travel time is roughly equivalent (Martensen and Nuyttens 2009). International data is lacking to estimate comparative risks of cycling per travel duration but this indicator may be lower than relative risk indicators based on travel distance. (Van Hout 2007) found that the relative risk of death per hour of travel was roughly equal between cyclists and car occupants in Belgium in 1999. Duration-based indicators of relative risk may be appropriate in instances where the duration of cycling and car trips is nearly the same — for example, in congested urban areas where cycling speeds are equal to, if not greater, than car speed.

Part of the “built-in” lack of safety of cycling is that the road system has, with some notable exceptions, not been designed for cyclists. More precisely, the road system has not been designed for mixing well-protected, heavy and high velocity vehicles with unprotected, lightweight and slower road users. Furthermore, the traffic system does not typically account for the specific characteristics of cyclists and bicycles. Cyclists are highly flexible and sometimes unpredictable road users, riders display very different abilities, cyclists seek to minimise energy expenditure, bicycles can be easily de-stabilised and are relatively difficult to see because of their size (in daytime) and their poor or lack of night-time lighting. Cyclists are also often seen by motorists as intruders in the road system.

Given the vulnerability of cyclists in traffic, those seeking to promote cycling must address a fundamental question: *do policies that increase the number of cyclists contribute to less safety and more crashes?*

This is an important question because if cyclists are vulnerable and the road system is not designed for cycling, then pro-cycling policies could conceivably expose a greater number of people to potentially dangerous conditions. The short answer to this question is that when the number of cyclists increase, the *number* of crashes, both fatal and non-fatal, may increase as well – *but not necessarily so* if attention is paid to good policy design. Furthermore, the incidence *rate* of cycling crashes may decrease, *especially if accompanying safety-improving policies are implemented.* Thus while the number of crashes may increase, cycling safety -- measured by the number of crashes per some measure of exposure (e.g. trips, cyclists, time cycling, distance travelled) -- may improve. A fuller answer to this question must address four crucial factors whose understanding is essential in the cycling safety debate:

- The linkage between cycling, safety and health
- The safety in numbers effect
- The strong under-reporting bias in cycling crash statistics
- The lack of adequate exposure data

1.2. Linkages between Cycling, Safety and Health

A discussion of the impact of cycling on road safety should not be isolated from a broader discussion of the overall health impacts of cycling. Indeed, if we are concerned that increasing the number of cyclists may increase crash numbers or risks, it is because of the deleterious effects of crash-induced injuries on cyclists' health. Injuries from crashes, however, are not the only health endpoint from cycling – exposure to air pollution can negatively impact cyclists' health just as cycling-related exercise can (greatly) improve cyclists' health. Pursuing *increased safety* for cycling (e.g. reducing crash risk and the severity of crash outcomes) makes sense no matter what the balance of positive/negative health outcomes from cycling since these policies expressly reduce the negative outcomes linked to crashes. Understanding the balance of positive/negative *health* outcomes from cycling, however, is essential in helping frame efforts to *increase cycling*.

Health benefits of cycling: Physical Activity

The World Health Organization recommends that adults participate in at least 30 minutes of moderate exercise 5 days a week and more intensive training a few times every week. Cycling, as a moderate physical activity, can significantly reduce clinical health risks linked to cardiovascular disease, obesity, Type-2 diabetes, certain forms of cancer, osteoporosis and depression. Taken separately and even more so when effects are cumulative, these conditions exact a high human and economic cost on society. This health improving-effect is robust across different studies and in different geographic contexts (Tables 1.2 and 1.3). There is evidence that the range of morbidity-reducing effects are significant as well – not only does cycling reduce disease-related *deaths* for cyclists but it also contributes to substantially better *health* (Rabl and de Nazelle 2012).

Health Impacts of Physical Inactivity

"Physical inactivity is one of the most important health challenges of the 21st century because of its influence on the most deadly chronic diseases, contributing worldwide to 21.5% of ischemic heart disease, 11% of ischemic stroke, 14% of diabetes, 16% of colon cancer and 10% of breast cancer (Bull, et al. 2004). The World Health Organization (WHO) recently estimated overweight and obesity to be responsible for 2.8 million deaths annually; physical inactivity is (separately) responsible for an additional 3.2 million deaths."

Source: (de Nazelle, et al. 2011)

Table 1.2 **Quantified relative risk of all-cause mortality for cyclists compared to non-cyclists**

Relative risk expressed as a ratio of *all cause mortality of cyclists* compared to non-cyclists after controlling for confounding factors (age, gender, education, etc.) – e.g. a relative risk result of 0.70 indicates that a cyclist has a 30% reduction in risk of death compared to a similar non-cyclist.

Location	Relative mortality risk (cycling/non-cycling)	Confidence interval	Study
Copenhagen, DK	**0.72**	0.57-0.91	Anderson *et al*, 2000
China	**0.79**	0.61-1.01	Matthews *et al*, 2007
China (high activity)	**0.66**	0.40-1.07	Matthews *et al*, 2007
Finland	**0.78**	0.65-0.92	Hu *et al*, 2004
Finland (high activity)	**0.69**	0.57-0.84	Hu *et al*, 2004

Evidence suggests that this health-improving effect is not linear – that is, the greatest benefit for a sedentary person occurs simply from becoming active and further health benefits reduce with each additional increment of moderate activity (US DHHS 2008). Evidence of the non-linearity of benefits (e.g. the dose-response relationship) varies according to pathology and for some pathologies the relationship is unclear. Nonetheless, the evidence suggests that the health benefits of cyclists are greatest for those who were previously sedentary or displayed modest levels of exercise. It also appears that the health gains from physical activity are greater for frequent and recurrent bouts of moderate exercise as opposed to occasional periods of higher-intensity exercise (Praznoczy 2012). Successfully attracting non-cyclists or otherwise inactive people will deliver the greatest health benefits from physical activity but will require a good understanding of their perceptions of safety (see Chapter 4) and of the specific safety challenges posed by inexperienced cyclists.

Table 1.3 **Quantified relative risk estimates for *selected diseases* from 2.5 hours per week of moderate physical activity***

Disease	Relative risk (exercise vs. sedentary) – Square root model	Study
Cardiovascular disease	**0.82**	(Hamer and Chida, 2008).
Colon cancer (men)	**0.87**	(Harriss, et al. 2009)
Colon cancer (women)	**0.91**	(Harriss, et al. 2009)
Breast cancer**	**0.87**	(Harriss, et al. 2009)
Dementia	**0.82**	(Hamer and Chida 2009)
Depression	**0.86**	(Paffenbarger, Lee and Leung 1994)
Diabetes	**0.82**	(Jeon, et al. 2007)

* RR normalised to 2.5 hrs moderate physical activity in (Woodcock, et al. 2009)

** Linear model

Health benefits of cycling: Reduced air pollution

Some researchers suggest that a secondary health benefit from cycling (not just for cyclists) may be the improvement of local air quality due to bicycle traffic replacing other, mostly car-based, travel. Replacing short car trips with cycling or walking could result in a disproportionate reduction of volatile organic compounds (VOCs) and fine particulate matter emissions since a large share of these emissions are emitted in the first few minutes of motor vehicle operation (e.g. cold-start emissions) and thus over distances easily replaced by bike trips (Grabow, et al. 2012).

While the potential for air quality-related health improvement is important, the extent to which this benefit is realised depends on how successfully pro-bike policies reduce a significant share of car travel. The realisation of this potential also depends on the emissions profile of cars whose trips are susceptible to being replaced.

With the exception of the Netherlands and Denmark, and some specific urban areas, it is not clear that pro-cycling policies have led to a significant reduction of car traffic, at least at present. One reason for this is that, at least initially, new cyclists seem to switch not from cars but from public transport and walking. For instance, (Börjesson and Eliasson 2011) find in a survey in Stockholm that only 13% of cyclists identified the car as their second-best travel alternative. Likewise, only 10% of Barcelona’s Bicing users, 5%.of Lyon’s Vélo’v users and 2%[4] of Montréal’s Bixi users would have used a car absent bikesharing (Ajuntament di Barcelona 2007) (Beroud 2010).(Bachand-Marleau, Larsen and El-Geneidy 2011). The initial potential for mode shift seems low – in central Lyon and Villeurbanne, the public bicycle system Vélo’v was found to have replaced less than 0.01% of all car travel. However, it should be noted that car-bicycle replacement might be greater if measures are taken that reduce average trip distances (e.g. by increasing density) with a correspondingly larger health impact.

Air pollution health benefits from car trip reduction could potentially be more significant in areas with fewer walking and public transport opportunities (though these areas may be ill-suited for cycling as well). In areas undergoing rapid motorisation, air quality benefits from retaining cycling and walking shares could be high -- (Shaheen, et al. 2011) find that 16% of users of Huangzhou’s bikesharing system replaced car trips (78% for users from car owning households) and that 37% state they have postponed buying a car. Over time, if pro-cycling policies are sustained, new cyclists may indeed switch from cars. If that is the case, the health-improving impact from reduced air pollution may be positive but lagged though evidence is lacking on this point[5].

To be clear, reductions of pollutant levels (especially those of fine particulate matter, ozone (O_3) and NO_2) from automobiles and other motorised traffic[6] have been shown to have significant beneficial health impacts. What is less clear is the extent to which uptake of cycling will lead to strong enough reductions in motorised traffic such that these benefits are realised and research suggests that this is not the case (van Kempen, et al., 2010). As a general rule, it may be more appropriate to take into account air pollution impacts from switches from *public transport and walking* (rather than from mainly cars) to cycling when assessing the *initial* health impacts of pro-cycling policies.

Another factor to consider is the relationship between pollutant emissions and exposure to pollutants. Pro-cycling measures are often comprised of (or accompanied by) policies seeking to calm traffic, increase urban densities or mix land uses such that longer trips by car are replaced with shorter trips by foot, bicycle or public transport. When successful, overall pollutant emissions may decrease whereas exposure to pollutants may paradoxically increase. This is because of a shift in proximity between emission sources and people due to densification and from the configuration of high-density urban settings (e.g. increased incidence of “canyon” streets[7]).

Should pro-cycling urban design policies increase the incidence of stop-and-go traffic, local pollutant concentrations may also increase as a result of repeated engine acceleration. Evidence from a study in Vancouver confirms the paradox of higher density, more polluted neighbourhoods (under current traffic regimes) – dense, multi-use neighbourhoods (e.g. “walkable” or bicycle-friendly neighbourhoods) were found to have high levels of primary traffic-related pollution (NO) though secondary pollutants such as ozone were found to be lower[8] (Marshall, Brauer and Frank 2009). In these instances, the balance of overall health impacts may see the individual physical activity-linked health gain *for cyclists* be eroded by a collective air-pollution linked decrease in health for all other *inactive local residents* remaining in high density and relatively more polluted neighbourhoods. This of course is a sub-optimal outcome of urban policies and underscores the need to manage traffic volumes proactively and tackle pollutant emissions alongside urban policies seeking to increase density or shorten trips.

Where pro-cycling policies replace car trips, the air quality health benefit will be proportionate to the amount of displaced air pollution. New automobiles emit fewer and fewer air pollutants and considerable progress has been made to reduce disproportionately more polluting “cold-start” emissions. At the same time, ultra-low emission technologies, mainly in the form of hybrid drivetrains (and some battery electric vehicles), are penetrating many national fleets. This would seem to suggest that the marginal air pollution reduction benefit from car-bicycle trip replacement will decrease over time. However, if pro-bicycle policies successfully lead to the replacement of car travel by the most polluting and older vehicles in the fleet, the air pollution reduction benefit could be significant. There seems to be insufficient evidence at this time to quantify this potential impact.

Other health Benefits of cycling

Other potential benefits from increased cycling include a reduction in traffic noise and a reduction of crash injuries from modes previously used by new cyclists.

Noise is an important environmental stressor increasing the risk of ischaemic heart disease, contributing to cognitive impairment in children and disrupting sleep patterns (WHO 2011). Traffic noise is a significant contributor to overall noise levels and some have postulated that pro-cycling policies may reduce overall traffic noise. Not many studies have sought to quantify this effect -- one study that has undertaken this analysis has found the health benefits of reduced noise due to a shift from cars to cycling are minimal (van Kempen, et al., 2010). For the reasons exposed earlier it seems highly optimistic to expect that cycling will decrease ambient traffic noise levels such that there is a city-wide positive health impact – though localised noise reduction is entirely likely.

An additional health impact could result from a reduction in the number of crash-related injuries and deaths due to people switching from other modes to cycling. The sign and scale of this benefit is related to the crash rate for those modes and the severity of injuries incurred. It is also related to the risk profile of those making the switch. For instance, a switch from public transport to cycling is not likely to generate any benefit due to reduced crashes given that the former is typically safer than the latter. A switch from cars to cycling, on the other hand, would reduce fatalities linked to car crashes, especially if one includes pedestrians and cyclists hit by cars in addition to victims of car-only crashes. A study in the greater Paris region has sought to quantify this effect under various mode shift scenarios. It finds that a modest increase of cycling to 4% of trips from its current level of 2%, assuming that only 5% of new trips were previously made by car, would result in 0.4 fewer deaths per year compared to 5 new bicycle crash-related deaths. However, at a 8% mode share for cycling (comparable to the cycling mode share of several other European cities) and assuming 38% of new bicycle trips were previously made by car, avoided car-crash deaths would break even with new bicycle-crash deaths (Praznoczy 2012). This finding helps frame the eventual crash fatality impact of long-term pro-bicycle policies – at some point, avoided car crash deaths will outstrip newly generated bicycle crash deaths, *all else equal*. In reality, pro-bicycle policies should seek to reduce *all* crash deaths and so these findings should hopefully only serve to indicate that there is a dynamic and positive safety impact of switching bicycle traffic for car traffic.

Risk profiles matter as well as seen in data from the Netherlands in Table 1.4. Eighteen to twenty-four year-olds switching from cars to bikes would decrease their risk exposure for fatal crashes, at least in the Netherlands. An early estimate of the overall health impact (including crash risk and exposure to air pollution) from shifting from car travel to cycling also found that young males benefit most – largely because of their car crash risk profile (van Kempen, *et* al, 2010). On the other hand, sixty-plus year old drivers switching to cycling would greatly increase their risk exposure, all else held equal.

Table 1.4 **Average number of killed per 1 billion vehicular kilometres in the Netherlands from 2007 to 2009 and relative risk**

Age	18 - 24	25 - 29	30 - 39	40 - 49	50 - 59	60 - 74	75+
Cyclists	7.4	3.7	3.7	6.6	9.6	23.7	164.0
Car occupants	9.6	3.7	2.1	1.2	1.5	2.1	13.2
Relative risk, cycling vs. car	-0.23	-0.01	0.74	4.65	5.44	10.18	11.40

Source: SWOV, 2012

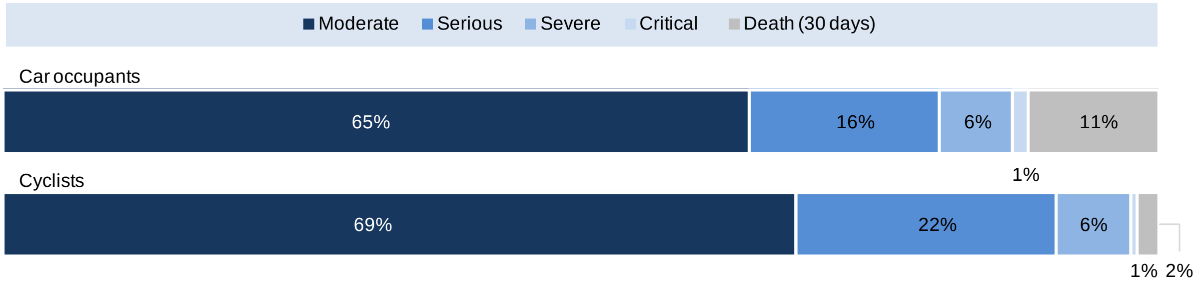
Health risks of cycling: Crash-related injuries for cyclists

Traffic infrastructure is seldom designed with safety as a starting point and though efforts are made to accommodate the wide range of behaviours displayed by road users, errors and unpredictable or impaired actions often lead to crashes. The kinetic forces involved resulting from the differences in mass and velocity of crash opponents largely dictates the severity of outcomes. Crash outcomes with cars are especially severe for vulnerable road users such as pedestrians and cyclists who by far lack the same level of protection mandated for, and offered to, car and other vehicle occupants.

The distribution of crash outcomes by severity varies across countries given the heterogeneity of cycling environments. For example, the share of killed and serious injuries (greater than MAIS 2 – or moderate injuries) is greater for cars than for cyclists in the Netherlands (Figure 1.2), principally because of a smaller share of deaths resulting from cycling-related crashes. In the UK, the opposite is true with those killed or seriously injured representing 16% of crash outcomes for cyclists versus 8% for car occupants[9].

The very young and the very old are disproportionately represented in serious crash-related injuries across a number of countries (see Chapter 4). Korea and Japan, two countries with a significant share of older people, are especially confronted with bicycle crash fatalities and injuries among the old – e.g. in Korea 65% of bicycle fatalities were aged over 60 (2009) and in Japan, 70% of bicycle fatalities were aged over 60 (average 2005-2010) – these figures are likely exacerbated by relatively low rates of car use and high rates of cycling (and walking) among these populations. For comparison, in the Netherlands, 55% of police-recorded bicycle fatalities were aged 60 and older (average 2005-2009) and in the United Kingdom, this figure was as low as 21% of all police-registered bicycle fatalities (2005-2010).

Figure 1.2 **Traffic injuries by severity in the Netherlands, Average 2007-2009**



Source: SWOV, 2012

Crashes between cyclists and other cyclists or pedestrians also are a source of injuries. Official German accident statistics indicate that in 2010 3 300 injury accidents occurred involving a cyclist and a pedestrian, and about 4 400 injury accidents occurred involving two bicycles. These types of crashes, because of their lessened severity, are often under-recorded . Nevertheless, such crashes appear to be a real issue in certain countries. In Japan, for instance, the Ministry of Land, Infrastructure and Transport decided in 2007 to reconsider their approach to cycling facilities in urban cores (where a large share of cycling occurs on sidewalks). Indeed, since 2000 a strong increase in crashes between cyclists and pedestrians had been noted leading transport authorities to start to develop separated one-way cycling tracks as a rule in urban cores.

Few studies have looked specifically at the crash-related injury burden among modes using metrics relating to overall lifetime health. Evidence from one study (in high cycling environments in Belgium) using disability-adjusted life years (DALYs)[10] finds that DALYs per 1 billion kilometres of travel was lowest for cars (113), followed by pedestrians (1359), cyclists (1724) and motorcyclists (6365). However, the relative contributions to lifetime health of years lost due to *disability* (YLD) versus *lost life* years (e.g. deaths or YLL) were found to be diametrically opposed for cyclists and car occupants. The majority of the health burden for cyclists was found to stem from *disability* (75% of DALYs) whereas *lost life* years represented 67% of the crash-related health burden for car occupants (Dhondt, et al. 2012).

Injuries to cyclists that do not require hospitalisation often do not appear in national or regional safety statistics and yet represent the majority of all cyclist injuries. Minor crashes, exact a high cumulative cost, when considering health care expenditures, absenteeism and lost productivity (B. de Geus, et al. 2012) (Aertsens, et al. 2010).

Few studies have looked specifically at the incidence rate of minor versus major crash outcomes for cyclists but evidence indicates that un-recorded minor injuries represent the overwhelming majority of cycle crash outcomes. One cohort study of bicycle commuters in Portland, Oregon found that 80% of all injury-causing crashes were classified as “minor”, e.g. requiring no medical attention. That study found the incident rate for minor versus serious (e.g. requiring medical attention) injuries was found to be 0.093 and 0.024, respectively, per 1000 kilometres (Hoffman, et al. 2010). Another cohort-based study from the Netherlands found an even greater share of “minor” crash outcomes – 97% of the total[11] – though this result cannot be compared to the Portland case given that a “minor” incident was defined as one requiring less than 24 hours hospitalisation. Corresponding incident rates for minor versus serious injuries per 1000 kilometres was found to be 0.046 and 0.001, respectively (B. de Geus, et al. 2012). (Aertsens, et al. 2010) find the cost of these accidents to be significant in Belgium – 0.125 euro per kilometre with productivity losses dominating.

Single bicycle crashes (e.g. crashes with no crash opponent) are also a significant source of injuries though they tend to go unreported in national statistics due to their lessened severity. Single bicycle crash outcomes involving falls and collisions with obstacles can result in especially serious injuries for elderly cyclists. Studies compiling hospital and police records reveal that, at least in countries with a high share of cyclists, single-bicycle crashes represent a majority of cyclist crashes and a significant share of overall traffic crash victims. e.g. three quarters of all cyclist crash victims in the Netherlands (P. Schepers 2012) (Schepers and Klein Wolt 2012), 87% of cycle crash victim in Flanders and Brussels (Dhondt, et al. 2012) based on hospital data and 73% of crash injuries in a prospective cohort study in Belgium(B. de Geus, et al. 2012).

Do countries with lower cycling shares display the same level of single bicycle crashes? Evidence looking beyond police-reported statistics is sparse on this point though one prospective cohort study in North America reports that 62% of injury-causing cycling crashes involved neither a motor vehicle or another cyclist (Hoffman, et al. 2010).

Health risks of cycling: Crash-related injuries caused by cyclists

While cyclists tend to fare badly in motor-vehicle crashes, cyclists themselves can injure other non-motorised crash opponents. The bulk of these crashes may have minor outcomes and go unreported but there is evidence that for certain crash opponents, especially elderly pedestrians and cyclists, outcomes are more serious (Chong, et al. 2009).

Health risks of cycling: Air pollution

Cyclists' are exposed to a wide spectrum of potentially health-damaging pollutants while riding. Foremost among these are constituents and products of motor vehicle exhaust -- especially particulate matter less than 2.5 microns in diameter ($PM_{2.5}$), ultrafine particulate matter (UFP) of less than 1 micron in diameter, NO_2 and O_3. Exposure to these pollutants are associated with heart disease, respiratory ailments and disease, lung cancer and mortality (Marshall, Brauer and Frank 2009) (Knibbs, Cole-Hunter and Morowska 2011). The dose-response relationship has been found to be linear (e.g. there are no threshold effects) with adverse health outcomes reported for long both long-term and short-term exposure (Marshall, Brauer and Frank 2009) (Weichenthal, et al. 2011) (Int Panis, Meeusen, et al. 2011). However, many studies have found that adverse impacts of air pollution in relation to mortality fall disproportionately on already-weakened populations such as the elderly or those with pre-existing cardiovascular conditions (Int Panis and de Hartog 2011). If the cycling population is largely drawn from younger and healthier subjects, then mortality-related impacts due to exposure to air pollution are likely to be smaller than those suggested by many studies. This would suggest that the health disbenefits from exposure to air pollution for cyclists may be overestimated in current analyses.

Box 1.2 **Electric Bicycles, Safety and Health**

Electrically-assisted bicycles and light scooters are not specifically addressed in this report, largely because national crash and injury data do not typically keep separate statistics for these vehicle classes. Nonetheless sales of electrically-assisted bicycles are growing rapidly in many countries. More than 32 million electric bicycles were sold in 2011, 31 million of them in China (and most of these were not strictly "pedelecs" as described below). In Europe and Switzerland over 750 000 electric bicycles were sold in 2011 with market shares of total bicycle sales reaching 15% in the Netherlands, 9% in Austria and 8% in Germany. Upwards of 350 000 electric bicycles were also sold in Japan in 2011 surpassing moped sales. The rate of uptake of electric bicycles and their continued penetration within national fleets warrants some discussion of their safety and health aspects.

The electric bicycle market can be broken into two broad categories. "Pedelecs" represent the first category and are characterised by low-power motors that operate only with pedal input up to speeds of ~25 km/hr at which motor assistance cuts out. They cannot be powered by the motor alone and in most jurisdictions are treated as traditional pedal-powered bicycles. The second category consists of pedal vehicles with more powerful electric motors, higher top-end speeds and, in many instances, the ability to operate solely on electric power (e.g. with no pedal input from the rider). The regulatory framework for these vehicles is disparate among countries and, in some cases, within countries. Some jusrisdictions (e.g. the EU) classify these types of electric "bicycles" as light motorcycles or mopeds triggering more stringent licensing, operating age and helmet use rules. Certain other jurisdictions are in the process of revising the regulatory framework governing these vehicles (as in the case of China). Below, we discuss safety and considerations in relation to *pedelecs* only.

Research on pedelec use is limited but the following characteristics can be summarised from the litterature; average per-trip travel distances tend to be longer than for traditional bicycles, average travel speeds tend to be higher and pedelecs tend to be used predominantly by those 50 and older and by commuters (Roetynck 2010) (Hendriksen, et al. 2008) (Lenten and Stockmann 2010). What do these findings imply as far as safety is concerned?

Increased speeds will translate into higher crash-related kinetic forces. This suggests that pedelec use may lead to more severe injuries than crashes involving a traditional bicycle. Available evidence supports this hypothesis (Lenten and Stockmann 2010) (GDV 2011) (Feng, et al. 2010). Higher speeds may also increase the severity of single-bicycle crashes and crashes involving bicycle and pedestrian opponents. The finding that older cyclists tend to be disproportionately represented among pedelec users also implies that crash outcomes will be more severe given the vulnerability of these cyclists in relation to the general cycling population. Crashes may also be more frequent for this class of user due to the combination of lower psycho-motor function and elevated travel speeds. The impact of speed on the frequency and severity of pedelec crashes could also be exacerbated should pedelecs attract new (and older) cyclists with little riding experience. Pedelec and electric bicle kilometres travelled are likely less safe than bicycle kilometres travelled, all things equal, and this should be accounted-for in policy.

What can be said about the health benefits of pedelecs? Again, this is an area where little research has been undertaken but there is evidence to support the following statements. Pedelecs require some physical effort and therefore can contribute to beneficial levels of physical activity. How much depends on the speed at which pedelecs are operated. At typical operating speeds (22+km/hr for pedelecs, 15km/hr for traditional bicycles) metabolic effort is roughly similar (Lenten and Stockmann 2010). If pedelecs are operated at traditional bicycle speeds (~15km/hr), then the metabolic effort for pedelecs is lower than a traditional bicycle and so too are the health benefits from physical activity. However, air pollutant intake is also lower at lower rates of metabolic effort.

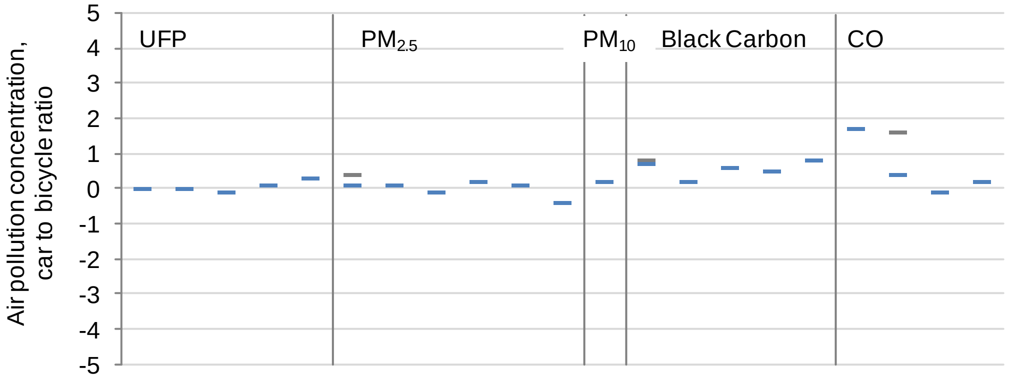
It would seem that increasing pedelec numbers is not neutral from a safety perspective and will require targeted action (possible strategies could include adapting bicycle infrastructure design, rider awareness campaigns , protective equipment) as well as more research. One may broadly conclude that pedelec riders face increased crash risk and increased risk of severe injuries as compared to traditional cyclists. Nonetheless, if pedelec riders were previously sedentary, the adverse health outcomes from crashes may be more than compensated-for by the health benefit of increased activity. A fundamental question remains as to the safety and health balance of pedelec use by older riders which should be a targeted research area in the future.

Are cyclists disproportionately at risk compared to other populations? Three variables come into play when evaluating this relative risk which is necessary to evaluate the health impact of shifting traffic to cycling. These variables are:

- ambient pollutant *concentrations* measured on or near the road,
- *exposure* to pollutants for on-road and near-road populations and
- the ultimate *dose* experienced by cyclists and other road users.

Most studies evaluating the health impact of traffic pollution are based on measurements of ambient pollutant levels in the roadside environment. One major reason for this is the relative ease and low cost of collecting this data. As a result, health risks to cyclists from exposure to $PM_{2.5}$ and UFP have often been downplayed in light of consistent findings that differences in average concentrations faced by cyclists and car drivers in traffic are rarely significant (and even slightly higher for car occupants, see Figure 1.3). Average concentrations do not serve, however, as a perfect proxy for gauging exposure or deposition.

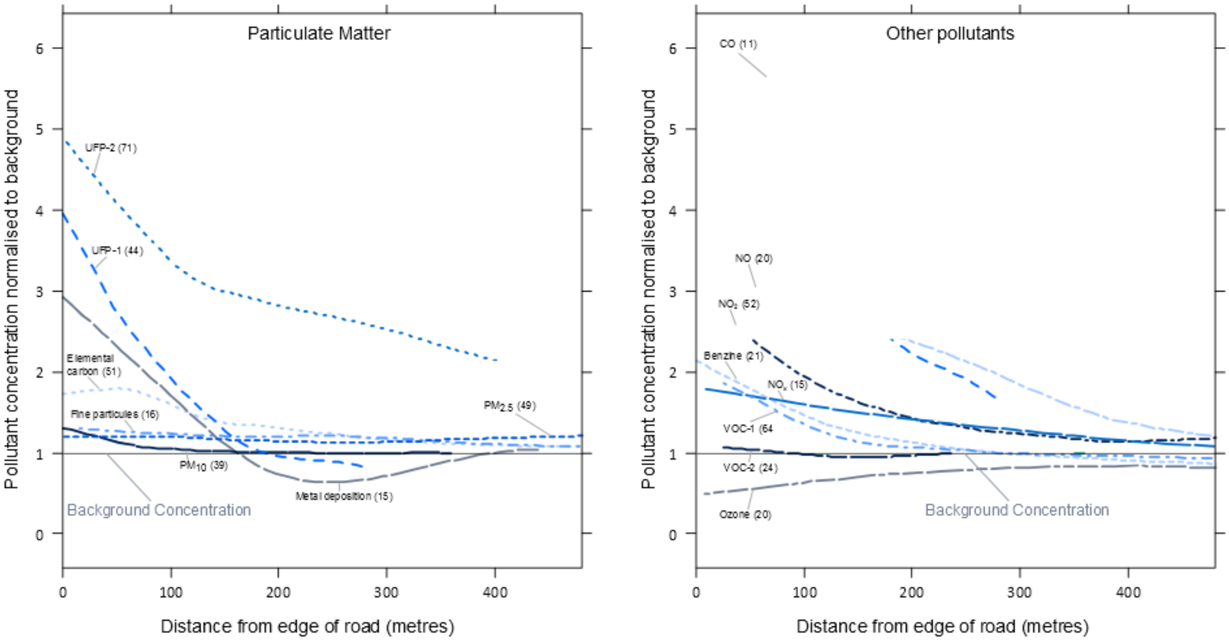
Figure 1.3 **Summary of car vs. cyclist pollutant concentration ratios, 13 studies, 21 findings**



Source: Compiled from (Brauer and Cole 2012)

Studies have confirmed a distance-based concentration gradient for several pollutant species that have significant adverse health impacts. The slope of this gradient is highly dependent on local conditions, fleet composition and meteorology but a recent review controlling for many of these factors has found that concentration-distance gradients for several toxic pollutants are relatively steep with highly dangerous ultrafine particulate matter and carbon monoxide degrading especially rapidly (Karner, Eisinger and Niemeir 2010)(Figure 1.4). This would suggest that dangerous pollutant concentrations faced by cyclists on near-road but separate facilities may be less on average than those faced by cyclists and motorists in the traffic stream.

Figure 1.4 **Pollutant concentration gradient from roadside – Local regression of background normalised concentrations on distance**



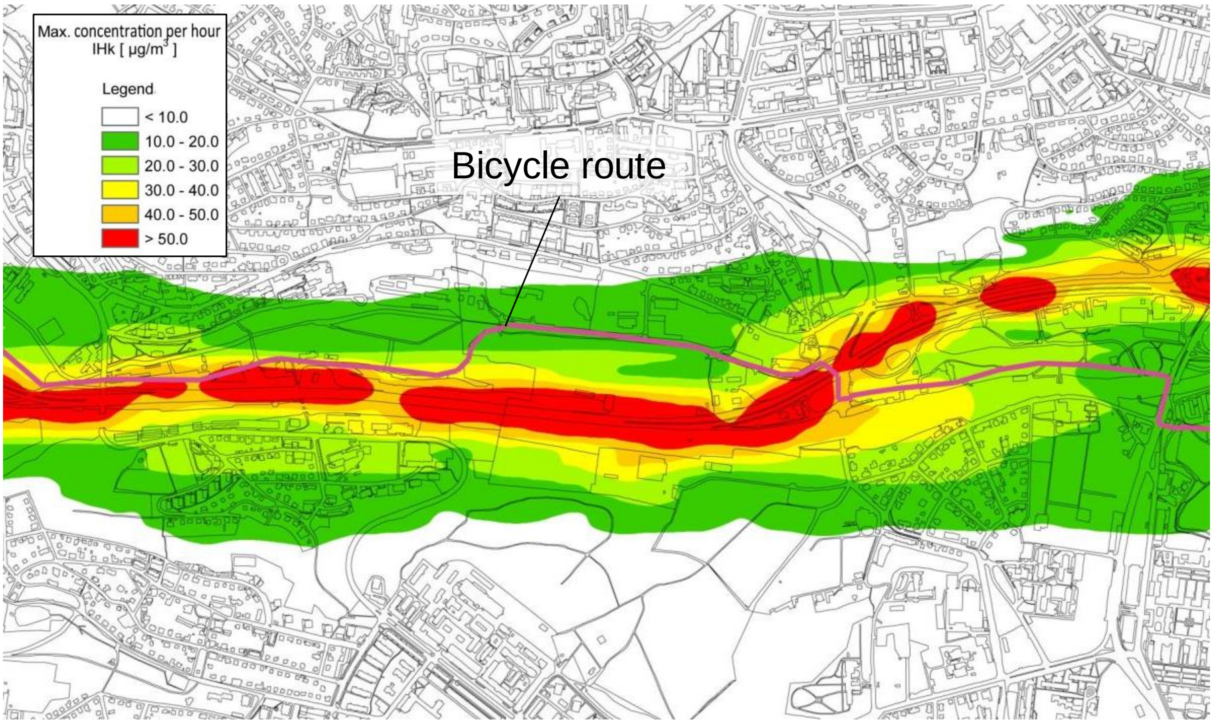
Regression sample for each pollutant in parentheses

Source: (Karner, Eisinger and Niemeir 2010).

This intuitive finding is supported by micro-scale studies looking at pollutant concentrations measured within very close distances to the roadway. For instance, (Kendrick, et al. 2011) found that displacing cyclists 1 to 2 metres away from motor traffic (in the context of a cycle lane to cycle track conversion) led to an 8-38% reduction in UFP concentrations depending on the day and location monitored. The particular configuration of the cycle track (separated from traffic by a row of parked cars and a small buffer zone) is likely to have played a role in the lower concentrations measured for cyclists in addition to the horizontal separation from motorised traffic.

Likewise, a monitoring study of a major roadway in Prague highlighted the distance-decay effect for road traffic pollutants (Bendl 2011). A cycling path running parallel, but not always adjacent, to the roadway registered levels of PM10 running from less than 10µg/m³ to higher than 40µg/m³ (Figure 1.5). These findings suggest that locating bicycle facilities even slightly further away from traffic may reduce pollutant concentrations faced by cyclists – especially if physical barriers help block pollutant dispersion (e.g. parked cars or planted barriers).

Figure 1.5 **Map of PM10 concentrations alongside a main road with 110 000 vehicles/day, Prague**



Source: (Bendl 2011)

Exposure to air pollutants is the product of ambient *concentrations* and *duration*. Holding concentration and distance equal, and assuming typical average speeds, cyclists experience greater exposure than car occupants since they require longer in order to travel the same distance. If traffic is congested however, cyclists may be as fast or faster than motor vehicles and thus cyclists' exposure, holding concentrations equal, may be lower. In reality, cyclists typically will, if possible, select lower trafficked routes that *de facto* reduce *exposure* due to lower pollutant concentrations despite sometimes longer travel times. In some cases, the exposition to harmful air pollutants is quite significantly reduced on low versus high traffic routes (Zuurbier, et al. 2010), (Cole-Hunter, et al. 2012).

The ultimate health impact of air pollutants on cyclists is closely related to intake and thus, ultimate deposition of pollutants in the lungs, especially in the alveoli where pollutants enter the bloodstream. Intake is a product of both *exposure* and, critically for cyclist, *ventilatory effort* since cyclists breathe more often and more deeply than occupants of motorised vehicles. Studies looking at ventilation-adjusted pollutant intake among cyclists and other road users find much higher doses for cyclists. Controlling for real measured ventilatory effort, one study found that cyclists inhaled 5.9 to 8 times more $PM_{2.5}$ (µg) than car drivers on the same route in the same traffic and meteorological conditions (Int Panis, Meeusen, et al. 2011). Another study found smaller but still significant differences with cyclists inhaling 1.9 times as much $PM_{2.5}$ (µg) as car drivers on the same route (Zuurbier, et al. 2010). Part of the difference between the two findings can be explained by the travel speed (and therefore ventilatory frequency and effort) of the cyclists – e.g. 12 km/hr in the former study versus 15/hr (for women) to 19km/hr (for men) in the latter. In Dublin, (McNabola, Broderick and Gill 2008) similarly find that cyclists register 1.4 times more intake of $PM_{2.5}$ than car occupants (and 1.3 times more than pedestrians but only slightly more than bus occupants) though their intake of volatile organic compounds is slightly less than car occupants (but more than pedestrians and bus occupants).

The three above-mentioned studies were undertaken in northern European settings (Netherlands, Belgium and Ireland) – do their findings hold for other geographical contexts? Cross-mode comparisons of pollutant exposure and intake including cyclists are not common, but two recent studies examine evidence from Spain and China. (de Nazelle, Fruin, et al. 2012) find in a pairwise analysis of travel along two commuter routes by various transport modes in central Barcelona that cyclists were *exposed* to 0.6 times fewer ultrafine particles as cars and about the same concentration of $PM_{2.5}$ (Table 1.5). Accounting for ventilatory effort (2.1 times as high for cyclists as for car occupants) but faster trip times for bicycles, they found that cyclists *inhaled* 1.7 times as much $PM_{2.5}$ as cars but about the same amount of ultrafine particles. They also find lower inhaled doses of black carbon and carbon monoxide for cyclists as compared to car drivers. Compared to bus occupants, cyclists registered *larger* inhaled doses for all pollutants considered while cyclists registered *lower* inhaled doses of all pollutants when compared to pedestrians.

Table 1.5 **Inhalation, travel time, air pollutant concentration and calculated inhaled dose: Pairwise analysis of two commuter routes in Barcelona**

			Ultrafine particles		**$PM_{2.5}$**		**Black Carbon**		**CO**	
unit	Inhalation Rate *($L\ min^{-1}$)*	Trip time *(min)*	Concentration (arithmetic mean) *($\#\ cm^{-3}$)*	Inhaled dose per trip *($\#\ x\ 10^9$)*	Concentration (arithmetic mean) *($\mu g\ m^{-3}$)*	Inhaled dose per trip *(μg)*	Concentration (arithmetic mean) *($\mu g\ m^{-3}$)*	Inhaled dose per trip *(μg)*	Concentration (arithmetic mean) *(ppm)*	Inhaled dose per trip *(μg)*
Walk	34.1	49	52700	89.8	21.6	35.1	6.31	10.7	1.31	7
Bike	41	25	77500	75.6	35	32.8	9.53	8.7	1.64	3.2
Bus	20	34	55200	39.8	25.9	18	7.58	5.3	2.14	3
Car	19.9	28	123000	75.6	35.5	19.7	19.5	10.4	7.33	8.9
Background			*19200*		*15.6*		*1.74*		*0.3*	
bike to car ratio	2.1	0.9	0.6	1.0	1.0	1.7	0.5	0.8	0.2	0.4
bike to bus ratio	2.1	0.7	1.4	1.9	1.4	1.8	1.3	1.6	0.8	1.1
bike to walk ratio	1.2	0.5	1.5	0.8	1.6	0.9	1.5	0.8	1.3	0.5
bike to background	..	..	4.0	..	2.2	..	5.5	..	5.5	..

172 trips, route length 4.7 and 3.1 km, 60% peak hour traffic, 40% off peak

Source: (de Nazelle, Fruin, et al. 2012)

Another recent study has looked at pollutant intake across various modes in Shanghai. It found that cyclists register a disproportionate pollutant intake compared to other travellers – peak hour inhalation doses of PM_1 for cyclists ranged from 2 times as great as for bus occupants and 4.25 times as great as for car occupants (using taxis as a proxy). Another finding was that absolute concentrations of particulate matter were substantially more elevated than those found in other studies in North American or European contexts (Yu, et al. 2012).

Overall, evidence on the concentration-exposure-deposition relationship suggests that cyclists' health could be improved by locating bicycle facilities away from road traffic where indicated – especially for sections where emissions are highest (motor vehicle acceleration on hills, long straightaways and in congested traffic) or where cyclist effort is greatest (e.g. hills). It also underscores the more elevated air pollution-related health risk faced by cyclists in highly polluted locales. Finally, when estimating air quality-related health benefits/disbenefits from a switch towards cycling, care should be taken to control for air pollution intake by mode as these can be quite different.

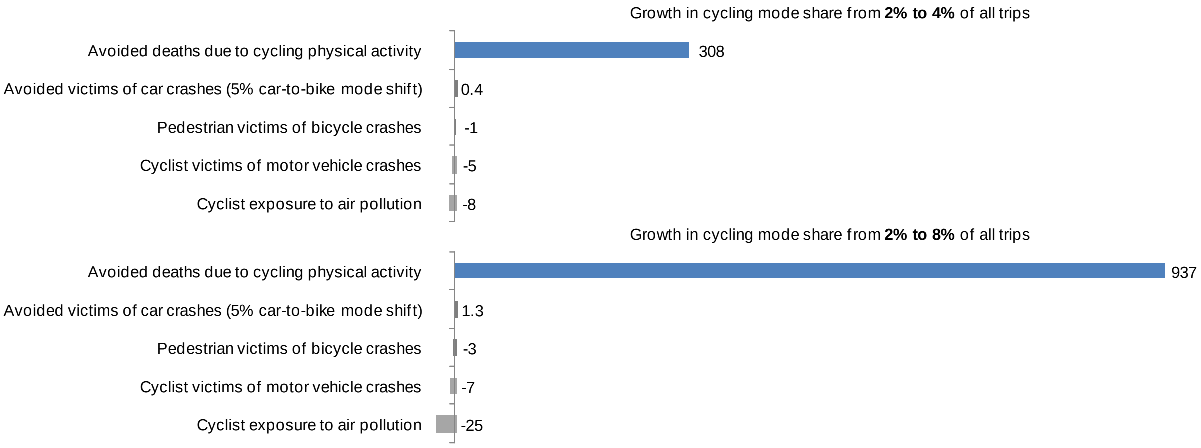
The balance of health and safety risks for cycling

Based on the wide range of research evidence highlighted in the previous sections, what can be said about the overall *balance* of health and safety risks for cycling? In particular, do the health benefits identified compensate for the injury risks linked to crashes and exposure to air pollution and noise? This is a particularly important question for cost-benefit analysis of cycling projects (see Box 3).

Several researchers have sought to answer these questions recently – (Praznoczy 2012),(Rabl and de Nazelle 2012), (de Nazelle, Niewenhuijsen, et al. 2011), (Teschke, et al. 2012), (Int Panis, Meeusen, et al. 2011), (Rojas-Rueda, et al. 2011),(de Hartog, et al. 2010), (van Kempen, et al., 2010). Controlling for exposure (and sometimes for crash under-reporting), these studies find that the health benefits of cycling are on average substantially larger than the disbenefits resulting from cycling crashes and exposure to air pollution.

In a comprehensive health and safety evaluation of cycling in the greater Paris region, (Praznoczy 2012) finds that the health impact of bicycle crashes impacts (in terms of fatalities) are particularly over-estimated by most actors whereas the health impact of air pollution is significantly underestimated. Crucially, however, the health benefits of regular exercise via cycling is several orders of magnitude higher than the health disbenefits outlined above and is fundamentally underestimated by authorities.

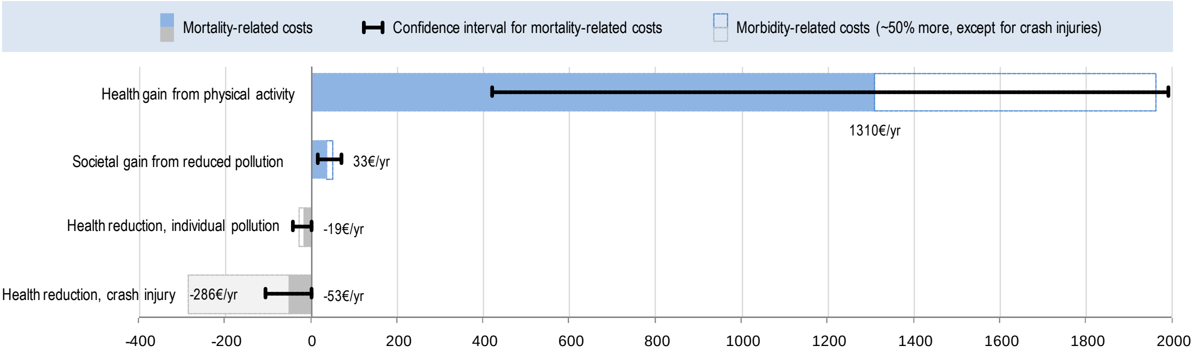
Figure 1.6 **Estimated mortality impacts due to an increase in cycle mode share in the Greater Paris region (annual deaths avoided/induced in 2020)**



Source: (Praznoczy, 2012)

Figure 1.6 summarises the findings of (Praznoczy 2012). Using conservative estimates[12] the study finds a benefit-to-risk ratio of 19 for an increase of cycling mode share in the Paris region from current levels to 4%, in line with recent growth rates. Should pro-cycling and other policies increase cycling mode share to levels found in many other French and European cities (8%), that ratio increases to 24. Under a more extreme scenario, but one in line with bicycle mode shares observed in some other (smaller) cities, that ratio could reach 27. As with other studies, it is the beneficial health impact from physical activity that by far outpaces other positive impacts and outstrips negative impacts. Unlike some other studies, and perhaps due to the high levels of suspended particulate matter in Paris, the author finds that the health impacts from cyclists' exposure to air pollution are greater than the crash risk cyclists face, at least in terms of fatalities.

Figure 1.7 **Estimated mortality (and morbidity) costs and benefits per individual switching from car to bicycle for work trips* in large European cities**



* 2x5km daily roundtrip, 5 days per week, 46 weeks per year

Error bars represent upper and lower (95% confidence intervals.

Source: Rabl and de Nazelle, 2012

Another study looking only at the monetised impact of switching from car to bicycle travel in large European cities (Rabl and de Nazelle 2012) finds that the positive health gains for an individual resulting from a switch from car to bicycle commuting add up to €1343 per year on average (Figure 1.7). It finds the negative health impacts, including those linked to crash-related mortality, result in a loss of €72/year – or 19 times less than the benefits. The study's principal finding that the health benefits from cycling surpass by several orders of magnitude other adverse health impacts linked to crashes and air pollution is robust to a range of assumptions regarding specific variables and monetary values. One reason is that physical activity has a beneficial impact on a much wider range of endpoints than air pollution and crashes. They note that considering *morbidity* in addition to *mortality* would likely increase individual and societal air pollution-related impacts by approximately 50% and increase the health gain from cycling by more than 50%. At the same time however, the burden from non-fatal bicycle accidents would also rise to €286/yr – or 5.5 times more than in the scenario outlined in Figure 1 using per kilometre costs from (Aertsens, et al. 2010).

While the studies cited above find that the health benefits of cycling far outweigh the disbenefits of increased crash risk – the crucial question remains "*which health benefits for whom?*"

Many of the studies cited above investigate primarily the *individual* health gains experienced by cyclists making the switch from *car use*. As noted previously, however, there is strong evidence that pro-cycling policies, at least initially, attract people that previously walked or used public transport rather than car users. There may be a point where the number of car users attracted to cycling significantly increases (evidence from countries with long-standing pro-cycling policies supports this) but it is unclear if, when and how many car users will make the switch as this is influenced not only by local policies but by local conditions as well. Suffice to say that at least the initial health impacts of pro-cycling policies will be largely based on of the uptake of cycling by pedestrians and public transport users rather than car occupants alone.

Box 1.3 **Accounting for cycling safety and health in cost-benefit analysis**

The use of cost-benefit accounting (CBA) in transport helps to guide investment decisions such that they maximize societal outcomes. Investments in cycling and the development of pro-cycling policies should ideally be subject to cost-benefit exercises, especially in a context of constrained budgets and a desire for maximum value. (Cavill, et al. 2008) review 16 CBA exercises that include or focus on cycling. Controlling for study methodology and quality, they find a range of largely positive benefit-to-cost ratios (BCR) in favour of cycling projects in 16 studies ranging from a BCR of 1.5:1 to a BCR of 32.5:1 with one slightly negative BCR. The median BCR for the studies examined was 5:1 which, for illustration, is much higher than the threshold 2:1 BCR required for infrastructure planning in the UK. Health benefits make up a significant contribution to the elevated cycling BCRs for cycling and walking projects in the studies examined. The authors note that the multiplicity of methods and variables considered as well as sometimes obscure assumptions included in the CBAs examined no not lend themselves to elucidating a clear view on the scale of cycling benefits. They also note the difficulty in observing levels of total physical activity for the populations considered (which would help to better gauge the health improvement impact for cycling) – though one study did control for leisure time activity (Rutter 2006). At a minimum, it would seem that more transparency is required regarding methodologies and assumptions in cycling-related CBA.

Given the preponderance of health benefits in cycling BCRs, it makes sense to ask the question whether or not these are *additional* benefits (e.g. external benefits not included in individuals' decision-making) or if cyclists already account for improved health in their decision to ride a bicycle (Börjesson and Eliasson 2011).

(Börjesson and Eliasson 2011) note that 4 factors must be considered when deciding whether or not health benefits from cycling should be include in CBAs for pro-cycling policies and infrastructure investment:

- whether or not cyclists derive health benefits from cycling,
- whether or not pro-cycling policies and infrastructure increase levels of cycling, preferably by sedentary people,
- substitution effects between cycling and other forms of physical activity, and
- the extent to which cyclists already account for health benefits from cycling.

This chapter already examines the first two points – individual health benefits are important and pro-cycling policies seem to, at least initially, principally attract non-car users (with geographic disparities). On the latter points, (Börjesson and Eliasson 2011) note that for most of the Stockholm cyclists examined in their study, cycling already represents their primary form of exercise and cite evidence that additional cycling would lead to a drop in other forms of physical activity. This suggests that time constraints may lead new cyclists (coming from other modes) to reduce other forms of exercise thus keeping constant levels physical activity. This would mean that cycling may not necessarily increase levels of physical activity (and thus health benefits) as much as many have assumed as suggested by some research (Yang, et al. 2012). However, it may increase the amount of regular moderate exercise that people get (as opposed to more concentrated but less frequent bouts of exercise) – this would have a health-improving effect (Praznoczy 2012).

Another matter is whether cyclists are aware of, and already account for, the positive health outcomes of cycling. If they do, then including health benefits as *additional* benefits in CBA would constitute double-counting. This has important implications since greatly minimising the health benefits from cycling in CBA, holding all else equal, would greatly reduce positive BCRs for cycling (Börjesson and Eliasson 2011)[13]. It seems unlikely that cyclists are fully aware of the health benefits of cycling and are able to accurately gauge these. However, it seems equally unlikely that cyclists completely disregard improved health as a reason for cycling. This suggests that defining *all* health benefits of cycling as *additional* benefits would seem unjustified. Nonetheless, the current state of knowledge does not allow for an accurate determination of what is and what isn't an additional health benefit from cycling for the purpose of CBA – indicating a need for additional research or, at a minimum, a need to expressly account for this lack of knowledge in CBA.

Another factor to consider is the extent to which health benefits attributed to increased physical activity via cycling remain as high when accounting for non-cycling physical activity. An increase in cycling does not necessarily imply an increase in overall physical activity or vice-versa. The studies cited above typically assume low activity levels for car occupants and health-improving increases in activity linked to cycling. This is a contestable assumption – car users may be physically active in other ways (e.g. sports activities) and pedestrians and public transport users may be nearly as active as cyclists. Car users switching to cycling may increase their activity levels or simply replace sports or other physical activities with cycling (Börjesson and Eliasson 2011) (Yang, et al. 2012). Likewise pedestrians and public transport users may simply replace one form of physical activity (walking) with another (cycling). Another factor to consider is how different countries or cycling populations may or may not be able to substitute cycling for different forms of exercise or vice-versa. It may be that populations whose cycling practice is mainly recreational may be able and willing to substitute cycling for other exercise whereas this may not be the case for populations whose cycling is (or would be) mainly transport-oriented and utilitarian (de Jong 2012). Any change in cycling levels would have a stronger impact on the latter population compared to the former. Overall, however, the fundamental question of how much cycling increases *overall* activity levels is a difficult one that remains largely absent from research.

Summarising the current state of research, we can say that on balance and even accounting for injury risk, cycling seems significantly health-improving when compared to car use by those with low physical activity levels. Policies that successfully lead to a switch towards cycling for this population may increase crash numbers (though not necessarily crash rates) but the adverse effects linked to this increase will likely be more than compensated for by a decrease in mortality and morbidity due to increased physical activity[14]. Increasing crash numbers would be nonetheless a negative policy outcome that must be addressed by specific measures. Conversely, policies that increase cycling but *do not* increase overall physical activity levels bring only risks (Int Panis and de Hartog 2011) though reducing these risks may lead to disproportionate benefits (e.g. by stimulating more cycling).

1.3. “Safety in Numbers”: Do more cyclists improve safety… and if so, how?

Researchers and observers have noted a correlation between an increase in the number of cyclists (or pedestrians) and a relative reduction of the incidence rate of severe/fatal crashes involving cyclists (or pedestrians). This “safety in numbers” effect (Jacobsen 2003) has been cited widely and would suggest that the relative risk ratios for cycling and other modes of transport illustrated in Table 1 are not fixed but change in relation to the modal composition of overall travel activity. The observed “safety in numbers” effect holds not only for multi-participant crashes but for single-bicycle crashes as well (P. Schepers 2012). At the centre of the phenomenon is the observation of non-linearity of risk: an increase of exposure (numbers, volumes, etc.) results in a less-than-proportional increase of the number of crashes (Elvik, 2009). Alternatively, the fewer cyclists there are in traffic (all else held equal) the greater the risk of crash and injury they face. In its most simplified expression, the observation of “safety in numbers” has led some to suggest that policies that increase the numbers of cyclists *de facto* increase safety since, per unit of exposure, the number of crashes decrease. This interpretation has limited use for policy since an absolute increase in crashes, irrespective of crash rate, is hardly a beneficial policy outcome and because the relationship between numbers of cyclists and crash rates is not necessarily straightforward nor uni-directional.

Care must be taken to not conflate observed *correlation* with *causality* when discussing “safety in numbers” as there are numerous plausible explanations for the observed phenomenon. On this note, there is strikingly little empirical research examining the causal factors that could explain the relationship between increased cyclist and pedestrian numbers and decreased crash rates. Hypotheses have been put forward that focus either on the behaviour of motor vehicle operators or, alternatively, on the behaviour of cyclists themselves.

“Expectancy” is one way of explaining “safety in numbers” from the perspective of car drivers. That is to say: if a road user (e.g. a car driver) expects the presence of another road user, or can predict the behaviour of other road users, one may expect lower risks (Houtenbos 2008);(Räsänen and Summala 1998). In this respect, it may be more exact to re-cast “*safety in numbers*” as “*awareness in numbers*” (F. Wegman in (Mapes 2009)). Another possible explanation is that cyclists are simply more visible to car drivers when they are more numerous (Bhatia and Wier 2012).

Researchers have suggested alternative explanations for the “safety in numbers” phenomenon based on hypothetic “crowd-sourcing” behaviour of cyclists themselves. According to this view, the more cyclists there are, the greater the number of individuals scanning the road environment for potential sources of danger and communicating what they detect to other cyclists either directly (verbally, hand signals) or indirectly (by taking observable avoiding action). Individual cyclists can benefit from the scanning behaviour of other cyclists such that larger groups of cyclists enjoy high levels of collective vigilance. In a similar fashion, cyclists may be collectively selecting routes (and possible riding behaviours) that are safer based on the leadership of more experienced cyclists (Bhatia and Wier 2012).

If “expectancy”, “awareness in numbers”, or “crowd-sourced” safety are valid explanations for the observed “safety in numbers” effect then one might reasonably assume that simply increasing the number of cyclists may indeed result in lower crash rates. At relatively high levels of cycling, it may even be possible that the absolute number of crashes could decrease as indicated by (Elvik, 2009).

However, the risk of confounding causal factors is great, especially when one considers the largely untested temporal direction of the observed “safety in numbers” effect. The explanation could simply be that cycle-safe traffic systems attract large numbers of cyclists – e.g. more people cycle when it is safe to do so. Large numbers of cyclists in the Netherlands, Denmark and Germany are associated with high densities of safe bicycle facilities which may explain why so many choose to cycle there and also why crash rates are relatively low. Without prospective or longitudinal studies looking at ex-ante and ex-post effects of new infrastructure, it will be difficult to determine if the effect observed is “*safety in numbers*” or “*numbers through safety*” (Bhatia and Wier 2012). If the latter explanation is correct, simply adding more cyclists to an unsafe traffic system may increase both absolute numbers of crashes alongside crash rates – clearly an unwelcome outcome.

From the lack of strong evidence on the behavioural or infrastructure-related determinants of “safety in numbers”, it would seem that great care should be taken in using the observed phenomenon as a basis for bicycle safety policy. At a minimum, policies seeking to increase the number of cyclists should be accompanied by robust risk-reducing actions.

1.4. Challenges to assessing cycling safety: Cyclist crash under-reporting and lack of exposure data

In the course of this review of cycling safety, it has become clear that most national authorities and many regional/municipal authorities simply lack an adequate basis on which to assess both cyclists' safety and the impact of "safety-improving" policies. Why is this? At the core of safety assessment is the calculation of crash incidence rates (typically split into fatal crashes and others of varying degrees of severity). Schematically; safety (expressed as the crash incidence rate) is the quotient of the number of crashes divided by a measure of exposure or bicycle usage.

$$\textit{Safety (incidence rate)} = \frac{\textit{Number of crashes, fatalities or injuries)}}{\textit{Measure of exposure (trips, km, hrs)}}$$

Box 1.4 **"Reporting on Serious Road Traffic Casualties" Key Recommendations**

The International Road Traffic and Accident Database (IRTAD) housed by the International Transport Forum at the OECD collects international crash and exposure data on a continuous basis. The International Traffic Safety Data and Analysis Group (known as the IRTAD Group) charged with piloting, expanding and improving IRTAD has underscored the problem of under-reporting on crash injuries and outcomes and in 2011 released the report "Reporting on Serious Road Traffic Casualties: Combining different data sources to improve understanding of non-fatal road traffic crashes" (IRTAD 2012). The report's main conclusions are especially relevant for reporting of cycling crashes given the high incidence of under-reporting of non-fatal injuries for cyclists. Below are those most relevant for improving the reporting of cyclists' injuries:

1. A complete picture of casualty totals (killed and seriously injured) is needed to fully assess the consequences of road crashes and monitor programmes
2. Injury information should complement information on fatal crashes to give a fuller picture of road crashes (especially in light of the high number of less severe injuries experienced by cyclists). Information on injuries should become more important for international comparisons.
3. Police data should remain the main source for road crash statistics. However, because of under-reporting problems and possible bias (for example with different rates of reporting for cyclists as compared to motorists), police data should be complemented by hospital data which are the next most useful source.
4. The data from hospital emergency departments, available in some countries, should be monitored regularly and researched to determine if they might shed more light on road casualties. This is especially important for cyclist traffic injuries since these are rarely linked to crash data.
5. The assessment of the severity of injuries should preferably be done by medical professionals, and not by the police at the scene of the crash.

Source: (IRTAD, 2012)

In many cases both numerator and denominator are inadequately measured or may be missing altogether. In practice, this means that many authorities do not have an accurate grasp of the rates of injury-causing cycling (and pedestrian) crashes. This is especially true for non-fatal crashes. Furthermore, in many cases authorities cannot clearly determine if observed trends in crashes result from a change in the *safety* of cycling or in the *number* of cyclists or the *volume* of bicycle travel. With many authorities seeking to increase rates of cycling and walking, it seems crucial that the factual basis on which policy assessment depends be improved.

Under-reporting of cyclist crashes

Overcoming under-reporting of bicycle crashes is an essential challenge for cyclist safety analysis. The underlying reason for under- reporting is that personal injury accidents are not systematically registered in many jurisdictions. In the context of the present report, it should be kept in mind that most of our analysis is based solely on data of *recorded* bicycle accidents – oftentimes from police records. Under-reporting is not limited to bicycle accidents or certain countries and, in a certain way, is inevitable and concerns all types of vehicles and all countries (IRTAD 2012). There is evidence, though, that among all road crash participants, cyclists are the least recorded (Broughton, et al. 2008), (De Mol and Lammar 2006).

Under-reporting is less prevalent when considering *fatal* crashes involving cyclists though there are discrepancies in criteria for attributing post-crash deaths to specific traffic incidents. Lack of coordination between police and hospital record-keeping also contribute to inexact crash-related fatality data. Under-reporting of *non-fatal* cycle crash related injuries is much more prevalent and further hampers road safety assessments (IRTAD 2012).

In principle, the police should always be informed of traffic-related personal injury accidents. However, in practice, not all road users conform to that obligation. There are numerous reasons for this. When there are no seriously injured persons or immediate physical complications (whiplash injury, light concussion, etc.), parties involved generally do not inform the police or, when informed, the police does not always go on the spot. The less serious the accident, the more probable the police does not intervene. When only vulnerable road users such as cyclists are involved, it is less probable that the police intervene than when cars are involved (Elvik and Vaa, 2004), (Vadenbulcke *et al*, 2009). Another reason for under-recording is the number of persons involved in bicycle accidents: the fewer people involved, the smaller the chance of official recording (Elvik and Vaa, 2004), (Vadenbulcke *et al*, 2009).

How severe is under-reporting of cycling crashes? Quite severe – a conservative assessment for Europe finds that police records only capture 50% of hospital admissions for traffic-related cycling injuries (De Mol and Lammar 2006). Another assessment for the United States finds this figure to be only 10%. (Pucher and Dijkstra, 2000). (Langley, et al. 2003) find that only 22% of cyclists seriously injured in a crash were recorded in official crash statistics in New Zealand. In Münster, (Juhra, et al. 2011) report that police records existed for only 34% of all cyclist injuries for a one-year study in 2009. An in-depth prospective cohort-based study for Belgium confirms strong underreporting of non-fatal crash-related injuries finding that only 7% of non-severe bicycle crashes were recorded in police statistics (B. de Geus, et al. 2012), (Vandenbulcke et al, 2009) – a low figure confirmed in other studies (Van Hout, 2007), (Elvik and Mysen, 1999).

Under-reporting complicates the analysis of long-term trends and hides the true picture of cycle safety. In particular, under-reporting impacts the assessment of:

- Evolution of cyclist safety: it is not known if and how under-recording has evolved over the years. In order to be able to reliably compare road safety factors over several years, the extent of under-recording should remain stable. In any case, each change in the number of crashes recorded, even annually, has an influence on crash statistics. This runs the risk that an increase or a decrease in statistics on bicycle crashes is strictly interpreted as such and not necessarily as a consequence of a change in the number of crashes recorded.

- Accident severity: crashes involving slightly injured persons are less well recorded than those involving seriously injured. The latter are less well recorded than those involving fatalities (i.e. death occurs within thirty days after the crash). This implies that amongst all road crash victims, the slightly injured are proportionally the most under-recorded and hence average bicycle crash severity is over-rated.

- Specific bicycle accident characteristics: as already mentioned, crash recording currently differs according to the types of crash opponents involved. At present, certain bicycle crash characteristics are proportionally less well documented than others. In particular, single-bike, bike-on-bike and bicycle-pedestrian crashes are likely strongly under-estimated, partly because of the reduced severity of crash outcomes.

- Overall vision on bicycle accidents: As the proportion of bicycle crashes in the overall number of road crashes is largely under-estimated, policy-makers face difficulty in correctly estimating the social implications of bicycle crashes (both in quantity and quality). This, in turn, hinders their ability to take appropriate measures. In the absence of an objective point of reference and comparison, it is also difficult to set quantified goals for reducing the number of cycling road accident victims.

Lack of bicycle usage and exposure data

Most countries and/or cities are ill-equipped to assess cycling safety because of a lack of accurate and detailed information on actual bicycle usage. The lack of exposure data is a real hindrance to understanding the current status of cycling safety and complicates the assessment of cycling policies. Crucially, exposure-based injury rates would allow authorities to understand if policies improve safety by *reducing exposure* (e.g. by decreasing bicycle use) which, given the benefits of cycling would be a bad thing or if they increase safety by decreasing crash-related injuries for a same level of usage.

Information about *how many* cycle crashes occur *is* useful for problem identification and allocation of resources. If substantial numbers of cyclists are injured, then there is a problem worthy of investigation and intervention. If many injuries occur in a particular situation then it is worth allocating resources to rectify the situation.

In contrast, *understanding* patterns of crashes and injuries requires that cycling exposure be considered. There are numerous possible exposure indicators including both direct and indirect or proxy measures (Wundersitz and Hutchinson 2008):

Travel surveys:

- Distance travelled
- Number of trips
- Time spent travelling

Traffic monitoring:

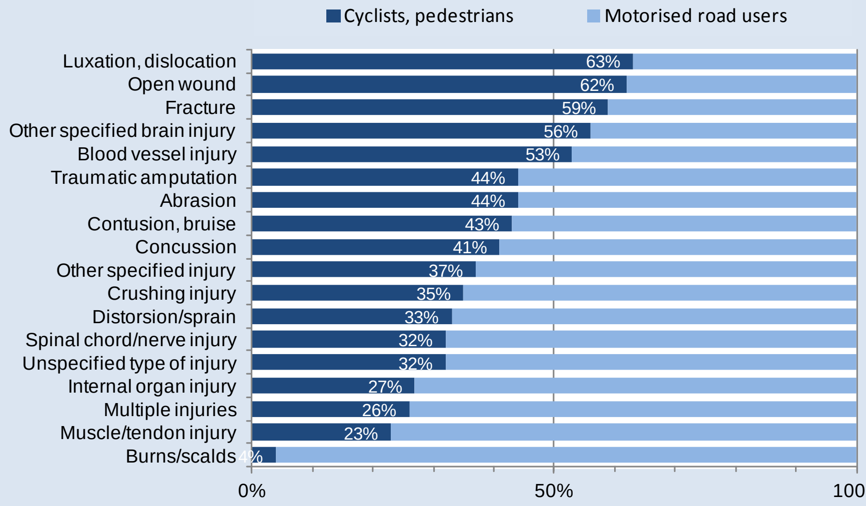
- Traffic volumes
- Traffic conflicts

Box 1.5 **Bicycle injury characteristics and reporting rates from the EU Injury Database (IDB)**

In Europe, police-reported crash data is centralised in the CARE database (see Chapter 4) which tracks several data points related to the crash participants, context, conditions, location and outcomes. In addition, the EU Injury database (IDB) collects standardised data on injury treatment from hospitals in the following countries: Austria, Denmark, France, Germany, Ireland, Italy, Latvia, Malta, The Netherlands, Portugal, Sweden and the United Kingdom. Traffic crash data in IDB supplements CARE police-reported statistics with more detailed hospital information on injury severity and treatment when linked via a common identifier number. However, most IDB bicycle crash data concerns crashes that are not reported to police -- or if they are, where no link has been made. IDB data can thus can serve as a good basis for understanding the scale and scope of injuries from bicycle crashes as well as to assess the extent of bicycle crash under-reporting in official statistics.

According to IDB injury statistics, cyclists represent 41% of all hospital-treated traffic injury patients in reporting countries and 30% of hospitalised traffic injury patients. Hospital length of stay for cyclists is about 7days – longer than the average length of stay for car occupants but shorter than the average stay for pedestrians and motorized two-wheelers. Upper body (37%), head injuries (26%) and lower extremity injuries (26%) dominate cyclist crash-related injuries. Head injuries for cyclists represent slightly more than the average for all injured traffic participants (24%). Cyclists have a slightly higher share of head injuries than car occupants (24%), a much higher share of head injuries than motorised two wheelers (16%) and a much lower share than pedestrians (30%). Cyclists have the highest share of upper body injuries of all road users reported in IDB. In terms of injury types, Cyclist and pedestrian injuries In terms of injury types, vulnerable road users dominate in 5 of 18 IDB-catalogued injuries – mainly traumatic force injuries (dislocations, open wounds and fractures) -- and a account for slightly higher share of overall non-concussion brain injuries.

IDB data on injury type for vulnerable road users versus motorized road users



Comparing IDB data with national police-reported crash statistics underscores the significance of bicycle crash under-reporting. In Austria, for example, official police-reported statistics report 5495 bicycle injury crashes in 2009. In contrast, IDB hospital statistics report 28 200 bicycle crash victim treated in hospitals which when accounting for travel survey data on private-practitioner bicycle crash consultations should be adjusted upwards to approximately 37 000 bicycle injury crashes. Police statistics only account for 15% of the total number of bicycle injury crashes in Austria in 2009 – a number consistent with other reported data on under-reporting of bicycle crashes.

Source: (Brandstaetter and Bauer 2012)

Arguably, the best measures of cycling exposure are distance, or time, cycled. In the absence of this information, proxy exposure measures can be used, but these are far less accurate. For example, length of cycling infrastructure in a particular country might give an indication of how much cycling occurs in that country. It is of course possible that a country has a great deal of cycling infrastructure that does not see much use. Other proxy measures include number of bicycles owned (some of which go unused, many of which may be used exclusively for recreation) and population (many of whom don't cycle). Rates calculated using less accurate indicators of exposure should be treated with caution.

This report has confirmed that most countries do not collect reliable information about distances cycled (i.e. cycling exposure) with which to calculate crash or injury rates (per kilometre travelled). This makes it difficult to answer questions such as how safe is cycling, and how does cycling compare to other modes of travel? Without information about distances cycled in different countries it is difficult to compare the safety of the cycling systems in those countries. Furthermore, without information about distances cycled under different circumstances it is difficult to answer questions such as how safe is cycling-specific infrastructure compared to cycling on roads without facilities for cyclists, and how safe is cycling during the day compared to cycling at night, and so forth? Without information about how much cycling is being done, statements about *how many* cycle crashes occur are of limited use.

Countries that do collect information about the volume of bicycle travel typically do so via relatively expensive national travel or mobility surveys based on interviews or panel travel diaries. Depending on the survey design, some surveys may under-report the level of cycling if respondents are asked to give only the main mode of transport used for a trip (for example, combined bicycle-public transport trips may be counted as public transport trips only if the latter segment dominates the former). The periodicity of travel surveys is not uniform across countries as well. Some countries, such as Denmark, the Netherlands and the United Kingdom, undertake yearly surveys, others undertake travel surveys much less often.

In the absence of distance, duration or trip-based indicators, proxy exposure measures can be used, but these are far less accurate. For example, length of cycling infrastructure in a particular country might give an indication of how much cycling occurs in that country. It is of course possible that a country has a great deal of unused cycling infrastructure, however. Other proxy measures include number of bicycles owned (some of which go unused or are used exclusively for recreational cycling) and population (many of whom don't cycle). Rates calculated using the less accurate indicators of exposure should be treated with caution.

Traffic surveys and traffic monitoring can also give a sense of the level of bicycle use – especially at the local or regional level or at the scale of a single facility. They also allow for more precise *ex-ante* and *ex-post* assessment of specific cycling safety measures. Additional reporting may also be helpful. For instance, the City of Copenhagen produces a biennial Bicycle Account that monitors the implementation of the city's cycling policies and highlights opportunities for further progress. Comparative cycling statistics can help compare performance among urban areas -- in the United States, the not-for-profit Alliance for Biking and Walking benchmarks the cycling and walking performance among 50 States and the 51 largest cities on the basis of comparable data sources.

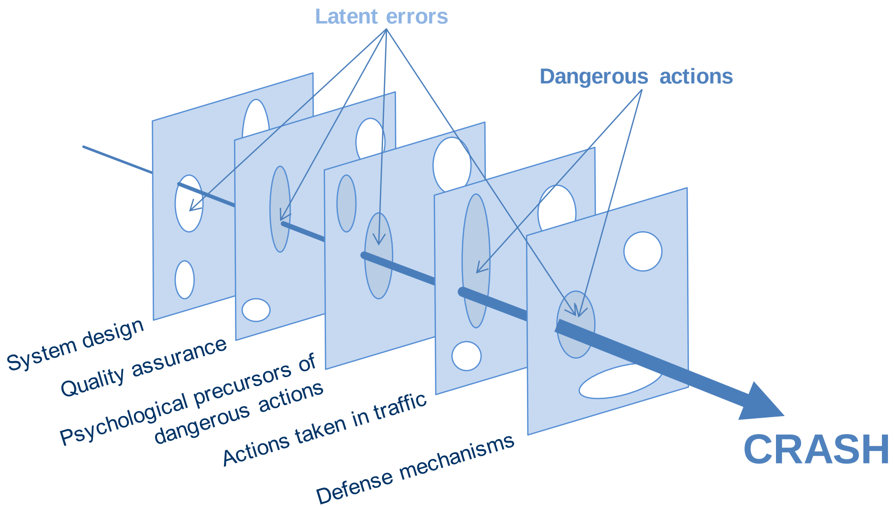
Various methods have been used in this report in analyses of crash patterns to accommodate lack of exposure information, and conclusions should be interpreted in the context of the shortcomings of these methods. More fundamentally, however, countries should begin to collect better exposure information if they do not already do so in order to guide future policies and assess their effectiveness.

1.5. How to deliver sustainable safety? The safe system approach

Based on the previous review of evidence, it would seem that on balance, more bicycle use will be beneficial for the health of individual cyclists and, given high rates of uptake, for the urban environment. Given what we know about the vulnerability of cyclists in traffic, how then should authorities design safety strategies encompassing all road users?

Authorities have often approached cycling safety (or all traffic safety) in a piecemeal and reactive approach – focusing alternatively on cyclists, pedestrians or other traffic participants and, rarely, on the entire traffic system. Reaching high levels of safety for cyclists (and other traffic participants as well) requires a more proactive approach that seeks to design (or re-design) the system to accommodate all road users and to account for their characteristics. This is especially true where policy would seek to preserve or increase cyclists' numbers. If the system is unsafe for cyclists, policy should focus on making the *system* safe, not just focusing on incremental improvements to cyclists' safety in an inherently *unsafe* system. The "Safe System" approach extends beyond cyclists only and has been recommended as a general safety planning approach for all traffic classes. Safe road systems incorporate strategies for better managing crash forces among disparate road users and should accommodate human error (OECD, 2008). The "Safe System" approach aims to reduce or eliminate crash risk by avoiding latent errors and dangerous actions in all phases of the traffic transport system (Figure 1.8).

Figure 1.8 **Schematic representation of the development of a crash**



Source: A. Djikstra, SWOV

One of the first iterations of the safe system approach was the "sustainably safe traffic" framework developed in the Netherlands starting in 1992 (Koornstra et al., 1992; Wegman & Aarts, 2006). At the heart of this approach is the notion that each category of road user knows what behaviour is required of them and what they may expect from other road users. This implies that the all aspects of the road environment should be made explicitly *recognisable* by each category of road user.

For infrastructure, the concept of "*recognisability*" in a sustainably safe traffic system rests on five crucial principles:

- Functionality
- Homogeneity

- Predictability
- Forgiveness
- State Awareness

We address each of these in turn below.

Functionality

Sustainable Safety’s “functionality” requirements are intended to intrinsically guide individual road users to choose a safe route, for themselves and also for others. The functionality principle of the traffic system is important to ensure that the actual use of the roads conforms to the intended use. Road systems should be separated into different functional groups (e.g. through roads, distributor roads, residential access roads and urban mixed residential/commercial streets). Each road or street should have one principal function; for example, a distributor road should not have any direct dwelling access so that users understand clearly what they can expect in that environment (e.g. mixed traffic, pedestrians and cyclists, spontaneous road crossing behaviour, etc. on mixed residential/commercial urban streets). According to the functionality principle, through-trips should not cross residential areas. Nor is it desirable to for cyclists to ride along an unsafe road too long. A large residential area is safe for internal motorised traffic as well as for cyclists and pedestrians. Too many junctions with the surrounding through roads should be avoided. There is a balance though -- an area that is too large leads to much internal traffic; one that is too small leads to many junctions with surrounding through roads.

For cyclists, the benefit of this principle is that motorised traffic will be concentrated on a limited number of main roads. Consequently, facilities for separating cyclists from motorised traffic can be concentrated on these roads.

Homogeneity

Road crash injuries stem from differences in speed and mass amongst crash opponents. The notion of homogeneity in road design is intended to avoid large differences in speed, direction, and mass by lowering traffic speeds to levels that are safe for all participants or, if this is not possible or desirable, by separating different traffic users based on their characteristics, mass and relative speeds. Based on this principle, traffic speeds where cyclists are present or are to be encouraged should be lowered to a safe (for cyclists and pedestrians) level, otherwise separate bicycle and motor vehicle facilities should be made available.

Table 1.6 **Safe speeds for different road types**

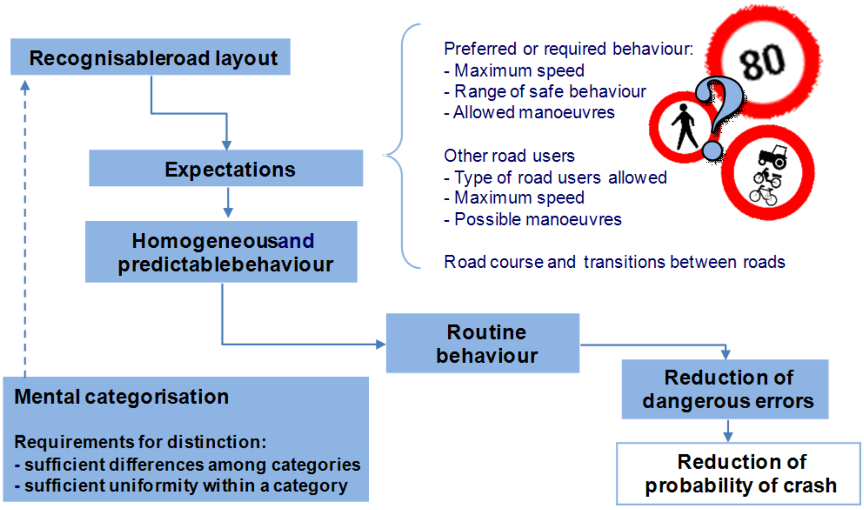
Road types	Safe speed (km/hr)
Roads with possible conflicts between cars and unprotected users (e.g. cyclists)	≤ 30
Junctions with possible lateral conflicts between motorised users	50
Roads with possible frontal conflicts between motorised users	70
Roads with no possible frontal or lateral conflicts among motorised users	≥ 100

Source: A. Djikstra, SWOV

Predictability

The design of the traffic environment (including the road and its surroundings) should increase the recognisability, and therefore the predictability, of traffic situations that may occur (Figure 1.9). Undesirable traffic situations can thus be acknowledged and avoided in time. In particular, a predictable road environment reduces distracting searching behaviour on the part of road users, and maximises the use of uniform and recognisable design treatments so that users intuitively know what to expect and what is expected of them. This is particularly important for cycling infrastructure design and treatments as these are less harmonised internationally than for motorised traffic. Limitation of the number of road categories makes the largest contribution to predictability. Furthermore, the differences between road categories should be large, while the differences within a road category should be small. In a predictable road environment, road users can concentrate on their main driving/riding task and conflict can be detected at an early stage.

Figure 1.9 **How "predictability" works to reduce crash risk**

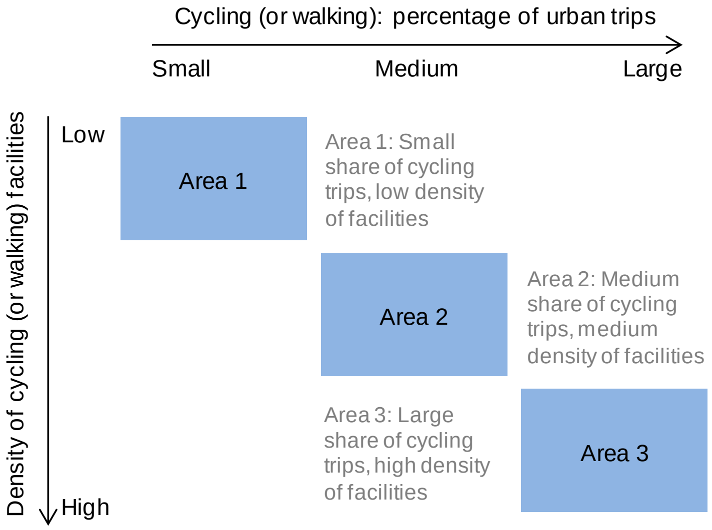


Source: A. Djikstra, SWOV

Forgivingness

If a crash cannot be avoided, the fourth principle, forgivingness, is meant to prevent a serious outcome of the crash. For cyclists, this means removing possible obstacles in the cycling environment as well as ensuring that cycling and road infrastructure design takes into account motorist behaviour (vis-à-vis cyclists) and the likely behaviour of cyclists themselves (e.g. reluctance to stop and lose momentum).

Figure 1.10 **Bicycle facilities and bicycle share**



Source: (Danish Road Directorate, 1998)

State awareness' of the road user.

Finally, a Safe System approach should include a component linked to the road users' ability to assess their capacity to handle the driving or riding task. This means that cyclists should be trained to handle a bicycle, but as well to use a bicycle in a mixed traffic environment. This may take place at an early age (safety in cycling classes) but should not be neglected for new adult cyclists or those not having any prior experience cycling in a traffic environment. This principle inherently recognises that there is no single type of cyclist - there are old and very young cyclists, experienced and inexperienced cyclists, commuting and recreational cyclists, etc. High impact safety policies should account for this heterogeneity.

Safe Systems in line with local conditions

Municipalities, regions and countries display different levels of bicycle use. They also differ in the degree to which they provide facilities for cyclists. The type of cycle facilities offered should depend on the share of cycling -- the more cycling, the more bicycle facilities (Danish Road Directorate, 1998). Facilities typical for a high share of cycling do not fit in a traffic environment with a low share, while facilities belonging to a low share are not compatible with a high bicycle share (Figure 1.10). Setting facilities within their context can help avoid "over" or "under" investing in safety.

Key Messages

- Many jurisdictions have or are putting in place pro-cycling policies and yet evidence points to the vulnerability of cyclists in road traffic. Do policies that increase the number of cyclists contribute to less safety and more crashes?

- The short answer to this question is that when the number of cyclists increase, the number of crashes, both fatal and non-fatal, may increase as well – but not necessarily so if attention is paid to good policy design.

- Furthermore, the rate of cycling crashes may decrease, especially if accompanying safety-improving policies are implemented.

- Many authorities are poorly equipped to assess the impact of pro-cycling and cycling safety policies as data on bicycle crashes is biased by under-recording and few authorities, especially at the national level, collect adequate exposure data necessary to understand crash rates in relation to bicycle usage.

- There is an observed safety-improving effect correlated with large numbers of cyclists however this “safety in numbers” or more precisely “awareness in numbers” effect cannot be shown to be causal – pro-cycling policies should seek to increase safety and not just the number of cyclists.

- Cycling safety should not be disassociated from the overall health impacts of cycling. Pursuing increased safety for cycling makes sense since these policies expressly reduce the negative outcomes linked to crashes for those *already* cycling. Understanding the balance of positive/negative health outcomes from cycling, however, is essential in helping frame efforts to *increase* cycling.

- Robust and consistent evidence indicates that the health benefits derived primarily from physical exercise due to cycling outstrips by several orders of magnitude the negative health outcomes for cyclists linked to crashes and exposure to air pollution. Pro-cycling policies have a largely beneficial impact on society despite higher crash rates than cars or public transportation.

- As far as crash outcomes are concerned, two, not incompatible approaches, present themselves.

    - The first is to attenuate the severity of crash outcomes in an otherwise dangerous system by, for instance, focusing on protective equipment for cyclists and vehicles, and

    - The second is to make the road environment itself safer via a “Safe System” approach that focuses on speed management and reducing the possibility for unequal (in mass, speed and behaviour) crash opponents from coming into contact with one another in the first place.

Notes

1. Absent other accompanying policies, it is not at all clear that pro-cycling policies *alone* can reduce congestion and pollution since newly released roadway capacity may be taken up by automobile traffic.
2. The 2004 report "National Policies to Improve Cycling" (ECMT, 2004) highlights the motivations behind national efforts to increase cycling.
3. Cycling was found to be 2.5 times more deadly per billion kilometres of travel including motorway travel by cars and 2 times more deadly per billion kilometres of travel when excluding motorway travel by cars.
4. 10% if including taxis.
5. Pro-cycling policies are also credited with congestion reduction benefits. For the same reasons outlined above, these may be (greatly) overestimated; at least insofar as road congestion is concerned. Nonetheless, there may very well be a not-inconsequential public transport congestion reduction benefit linked to pro-cycling policies that successfully attract new riders.
6. Evidence indicates that fine particulate matter emitted by internal combustion engines is more toxic than background levels of fine particulate matter (Laden, et al. 2000) – this suggests that a reduction in ambient levels of particulate matter emitted by motor vehicles would have a disproportionate and beneficial health impact.
7. This suggests that the installing bicycle facilities that severely reduce or eliminate polluting vehicles from such streets would reduce pollutant exposure, at least locally.
8. Consistent with the time-lagged nature of the formation of ozone. By the time primary pollutants are transformed into ozone, the pollutant plume will have moved downwind away from emission sources.
9. http://www.dft.gov.uk/statistics/releases/reported-road-casualties-gb-main-results-2010, accessed 10 September 2012.
10. Disability-Adjusted Life Years (DALYs) are defined by the World Health Organization as the sum of life years lost (YLL) and years of poor health (YLD) linked to health burden. One DALY can be interpreted as "one lost year of healthy life".
11. and one third of *overall* crash victims.
12. Lower bound of car-to-bicycle mode shift and lower bound of air pollution-related deaths.
13. (Börjesson and Eliasson 2011) note that while the case for full inclusion of health benefits as *additional* benefits in CBA may be overstated, they find that cyclists' high values of time in their study and the low relative cost of cycling infrastructure still imply positive BCRs for cycling infrastructure investments.
14. This finding, however, should not be seen as a way of minimising the importance of reducing crash rates

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