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The mortality impact of bicycle paths and lanes related to physical activity, air pollution exposure and road safety

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Abstract

Objective

Guidelines for bicycle infrastructure design tend to consider safety issues but not wider health issues. This paper explores the overall health impact of bicycle infrastructure provision, including not just road safety impacts, but also the population health impacts stemming from physical activity as well as cyclists’ exposure to air pollution.

Data and methods

We have summarised key publications on how bicycle paths and lanes affect cyclists’ exposure to physical activity, air pollution, and road safety. The health impact is modelled using all-cause mortality as a metric for a scenario with new bicycle lanes and paths in a hypothetical city.

Results

The outcomes of the study suggest that, based on currently available research, a reduction of all-cause mortality is to be expected from building bicycle lanes and paths along busy roads with mixed traffic. Increased physical activity through more time spent cycling is the major contribution, but is also the most uncertain aspect. Effects related to air pollution and cycling safety are likely to reduce mortality but are small. The overall benefits are large enough to achieve a high benefit-cost ratio for bicycle infrastructure.

Conclusions

The introduction of bicycle paths and lanes is likely to be associated with health benefits, primarily due to increased physical activity. More research is needed to estimate the absolute size of the health benefits. In particular, evaluations of the effects of bicycle infrastructure on time spent cycling are limited or of insufficient quality to infer causality. We recommend before-after studies measuring the effects of different interventions and in areas representing a wide range of base levels of cycling participation.

1. Introduction

Bicycle infrastructure along distributor roads (separated bicycle paths, see Figure 1; and marked lanes, see Figure 2) has been suggested as an effective means to encourage cycling and thereby improve health at the population level (Handy et al., 2014; Heinen et al., 2014; Hoehner et al., 2005; Pooley et al., 2013; Pucher and Buehler, 2010), but the application has been debated by adherents to so-called "vehicular cycling". The term "vehicular cycling" was coined by Forester to suggest that "cyclists fare best when they act and are treated as drivers of vehicles" (Forester, 2001b, page 557) meaning that they should share the road with other vehicles. They have opposed separate facilities such as bicycle paths and lanes for cycling because of safety concerns (Alrutz, 2012; Forester, 2001a; Pucher, 2001). On the other hand, guidelines in many countries are positive towards bicycle lanes within the carriageway for general traffic. For instance, the design guide by UK Department for Transport (2008) advises on-road facilities for roads with a large number of side road junctions because it reduces the potential for conflict at these locations. Such advice is supported by research suggesting that bicycle lanes improve cycling safety (Reynolds et al., 2009) as well as the perception of safety, for would-be cyclists (Fishman et al., 2012). Some agencies however caution against building physically separated bicycle paths (AASHTO, 1999, 2012; Department for Transport, 2008), based on worse road safety outcomes that have been reported in some publications (e.g. meta-analysis in the influential 'Handbook of Road Safety Measures', Elvik et al., 2009). Danish, Dutch and US guidance recommends 'truncating' cycle paths (converting it to a marked lane) before intersections to improve visibility and avoid conflicts (CROW, 2007; Jensen et al., 2000; NACTO, 2011).

Despite the dominance of cycling safety as an issue in design guidelines, an assessment of the overall health impact of bicycle infrastructure (including air pollution and physical activity) seems to be missing in the scientific literature. Such knowledge is also needed to economically valuate bicycle infrastructure and inform policy makers. The benefits of more time spent cycling (by existing and new cyclists) as a result of bicycle infrastructure improvements dominate in economic valuations (Cavill et al., 2008). The direct impact of bicycle infrastructure on road safety risks and air pollution exposure among all cyclists is often mentioned but has not yet quantitatively been included in economic appraisals (Cavill et al., 2008; Department for Transport, 2014; Lind et al., 2005; Sælensminde, 2004). Therefore, this paper sets out to compare the health impact of bicycle paths and lanes in relation to; 1) physical activity, 2) air pollution exposure, and 3) road safety among cyclists. The study focusses on the differences between bicycle infrastructure along distributor roads and roads without bicycle infrastructure (see Figure 3).

>>>> Insert Figure 1, 2, and 3 about here

Figure 4 depicts the pathways of new bicycle infrastructure to health impacts. The left box and middle box in the figure are concerned with the health impact related to increased time spent cycling (or walking). Cyclists run a greater risk of road crashes and they inhale more air pollution than drivers (Int Panis et al., 2010; Schepers et al., 2013) but the health benefits of increased physical activity outweigh those risks (De Hartog et al., 2010; Rojas-Rueda et al., 2012). Also, there are health gains for the general population (middle of Figure 4). Air pollution and risks of severe collisions are reduced to the extent that new bicycle trips replace trips by motor vehicles (Elvik et al., 2009; De Hartog et al., 2010; De Nazelle et al., 2011; Schepers et al., 2013). Various studies found the health effects of more cycling related to road safety and air pollution are small compared with the effect of increased levels of physical activity, even though different methodologies were used (De Hartog et al., Götschi et al., 2015; Rojas-Rueda et al., 2012; Woodcock et al., 2013). As we do not aim to repeat research on the health impact of increased bicycle use, we use the outcomes of the most recent meta-analysis by Kelly et al. (2014) on the risk of all-cause mortality in relation to time spent cycling and walking (active travel). In Figure 4, we included ‘time spent on active travel’ instead of cycling to include the possibility of an exchange between cycling and walking (see e.g. Fishman et al., 2015).

The health impact of bicycle paths and lanes will be more extensive than just health gains through more time spent cycling. In addition, these infrastructural facilities can alter exposure to both air pollution and road traffic injury risk and these effects apply to all (existing and new) cyclists (the right hand box in Figure 4). Effects on air pollution exposure and road safety risks may occur because these change at the location level due to bicycle facilities (Grange et al., 2014; MacNaughton et al., 2014; Thomas and DeRobertis, 2013). This is depicted in Figure 4 by an arrow from bicycle infrastructure to air pollution exposure and road safety risks. However, there is also an indirect effect via changed route choice because of bicycle infrastructure (Pucher et al., 2010), since air pollution concentrations and road safety risks differ between different road types (Jarjour et al., 2013; Schepers et al., 2013). This paper compares the relative size of the health impact of bicycle infrastructure among cyclists related to more time spent cycling (or walking), air pollution and road safety, the three most important factors for the health impact of cycling (De Hartog et al., 2010; Van Kempen et al., 2010). We restrict our analysis to mortality impacts as those related to morbidity are not as well understood (Kahlmeier et al., 2014; Kelly et al., 2014; Oja et al., 2011).

>>>> Insert Figure 4 about here

The remainder of the introduction describes literature related to the health impact of more time spent cycling, and exposure to the risks of air pollution and road safety, see Figure 4 for paragraph numbers. We use key publications such as review studies and meta-analyses, or estimates from single studies if those are not available. After an introduction describing data and methods in Section 3, the second part of the paper (Section 3), uses the synthesis of the literature as a platform to model the impact of a scenario with new bicycle infrastructure in a hypothetical Dutch city with 100,000 inhabitants having characteristics common in the Netherlands. The outcomes should be understood as an assessment of the average impact of bicycle infrastructure given the currently available evidence.

1.1 Effects of bicycle lanes and paths on mobility

1.1.1 Modal choice

Several review studies aimed to describe the impact of bicycle infrastructure on bicycle use (Heinen et al., 2010; Pucher et al., 2010; Scheepers et al., 2014; FHWA, 2015). These reviews reveal a lack of before and after evaluation to test the impact of a specific intervention and poor reporting of intervention characteristics that limits our possibilities to describe a dose-response relationship. The latter is of particular importance for this study, in order to be able to link new infrastructure to increased cycling. For instance, a correlational study like the one by De Geus et al. (2014) in Belgium shows a positive relationship between availability of cycle paths and commuting by bicycle, but the results are not suitable for deriving a dose-response relationship. Interestingly, a correlational study including over 40 US cities did yield a dose-response relationship. The study showed each additional mile of bicycle lane per square mile to be associated with an increase of approximately one percentage point bicycle modal share (Dill and Carr, 2003; Pucher et al., 2010), i.e. 1.6%/km/km^2 (as 1 mile equals 1.6km, the effect in kilometres is 1/(1.6/1.6^2)). However, correlation studies make it difficult to infer causality and assess the effect due to confounding factors such as surrounding land use. Evaluation research is extremely rare but is needed to determine the effect of bicycle paths on cycling (Pucher et al., 2010).

Barnes et al. (2006) estimated the effect on modal choice in Minneapolis-St. Paul, US, of routes installed with on-street bicycle lanes and standalone bicycle paths (of about an equal length) using before and after census data within a one mile buffer each side of the routes. The facilities increased bicycle mode share in their buffers by about 0.3 percentage points. Given the size of the buffer this would correspond to an increase of bicycle modal share of 0.6 percentage points for each additional mile of bike lane per square mile, i.e. 1%/km/km^2. The study did not explicitly separate the possible different effects of each type of facility, but the effects were slightly greater and more consistent for bicycle lanes.

We have not found other studies allowing for a description of a dose-response relationship for infrastructure interventions. However, knowledge of the results of other studies is important to tentatively judge whether the increased bicycle use found in the aforementioned studies can be generalized. A controlled natural experimental study by Goodman et al. (2013) found a significant increase of the modal share of walking and cycling for commuting and decrease of driving for commuting in response to new cycling infrastructure and cycle training in eighteen English towns. In a quasi-experimental study on the effects of new infrastructure by Heinen et al. (2015 a & b), it was found that high-quality infrastructure attracts users and that individuals who are more exposed to this intervention are more likely to change their mode of transport. Heinen et al. (2015b) analysed commute travel patterns based on a seven-day travel-to-work records of 470 adults collected before (2009) and after (2012) the introduction of the Cambridgeshire guided busway with a path for walking and cycling (the intervention). Individuals living closer to the busway were more likely to increase their share of commute trips involving any active travel by more than 30% and more likely to decrease the share of trips made entirely by car by more than 30%.

Goodman et al. (2014) evaluated a bridge for cyclists and pedestrians over a bay and a trunk road. Although the study was not about bicycle paths and lanes, it may be important that there were no signs that the increase in active travel as a result of these facilities was replacing other forms of physical activity. A before-after study of the Delft bicycle network in the 1980s is particularly important because it was conducted in the Netherlands where bicycle modal share is much higher than in areas where the aforementioned studies were conducted. The intervention included a total of 12 km of new bicycle paths, lanes, and standalone tracks, i.e. 0.9km/km^2 (the built up area of Delft is 13km^2). The plan also included two bicycle tunnels, three bicycle bridges, and authorisation of contraflow cycling (2.3km) to offer more direct routes. Bicycle modal share increased from 40% to 43% (Wilmink and Hartman, 1987). Comparing the outcomes of the studies by Dill and Carr (2003) and Barnes et al. (2006) would suggest an increase of bicycle modal share between 0.9% and 1.5% for an intervention of this size. The Delft study is not suitable to estimate the specific impact of bicycle paths and lanes, but the outcomes tentatively suggest that the impact of bicycle infrastructure on bicycle use is not necessarily smaller in areas where bicycle modal share is already at a high level. Another finding of interest to physical activity is that the time spent walking did not decrease after implementation of the Delft bicycle network (Katteler et al., 1987).

Other studies compared average daily cycle traffic on roads before and after building bicycle paths and lanes. While this before-after design with data acquired by counting users provides a better internal validity than a cross-sectional design, it has been suggested that these studies overestimate the modal share impact at an aggregate level. Pucher et al. (2010) refer to several before-after counts in North American cities and London but they warn that part of the increases that were found may be due to changes in route choice. Interestingly, it was found in Copenhagen (also an area with a high bicycle modal share) that average daily cycle traffic on streets equipped with bicycle paths increased by around 19%, while motorised traffic decreased by 10% (Jensen, 2006). The latter suggests that at least part of the effect is due to modal shift. Cycle lanes were associated with a smaller increase of bicycle traffic of some 6% and no significant change in volumes of motor vehicles (Jensen, 2006). More research is required to draw firm conclusions, but the increased volumes of cycling in response to bicycle infrastructure in studies in the Netherlands and Denmark (Jensen, 2006; Wilmink and Hartman, 1987) suggest that results found in countries with low volumes of cycling provide a first estimation of the impact in countries where volumes are already higher.

1.1.2 Route choice

Both revealed and stated preference studies suggest that cyclists prefer bicycle infrastructure. For instance, in a study by Mulley et al. (2013) in Australia people indicated the following options as being equally attractive: 1km on a busy road without bicycle lanes, 2.3km on a busy road with bicycle lanes, and 2.9km on a busy road with paths shared with pedestrians. However, studies on cyclist route choice (revealed preference research) suggest that distance and travel time are the most important factors (Broach et al., 2012; Gommers and Bovy, 1987; Menghini et al., 2010). Moreover, cyclists balance their total journey length and route directness meaning that cyclists aim to reduce the number of turns (Broach et al., 2012; Hood et al., 2011; Raford et al., 2007). Revealed preference studies also report a preference for routes along roads with low motor traffic volumes, standalone bicycle tracks, bicycle lanes and separated bicycle paths, although their contribution to decision making is less important than distance and time (Broach et al., 2012; Gommers and Bovy, 1987; Howard and Burns, 2001; Menghini et al., 2010). This means that cyclists detour to use bike lanes or paths (Pucher et al., 2010).

Gommers and Bovy (1987) conducted the only before-after study to evaluate the impact on route choice of the above mentioned bicycle network in Delft using a survey of bicycle route characteristics with a map of Delft on which respondents could draw their route. Table 1 shows the results by the share of kilometres per road category before and after implementation of the plan. As the share is 100% for the before and after situation it controls for increased bicycle use (Gommers and Bovy, 1987). The right hand column in Table 1 shows the share of kilometres travelled by bicycle if the share on standalone tracks had remained stable. While the length of bicycle paths and lanes along distributor roads (‘stadswegen’) increased by less than 3% (6.3km relative to 235km of roads, of which 75km were distributor roads), the share of kilometres travelled by bicycle on bicycle paths and lanes increased by over 4%. This indicated that cyclists tend to prefer routes on bicycle paths and lanes over other road types.

>> Insert Table 1 about here

1.2 Effects of the measures on exposure to air pollution

There is no general consensus about which indicators best represent the adverse health effects of traffic related air pollution (TRAP) (Janssen et al., 2011). In order for pollutants to serve our health impact assessment, there should be sufficient evidence about the health effect of exposure and the concentration has to be linked to traffic shown by high concentration contrasts between background and street locations. The mortality impact of Particulate Matter (PM), Black Carbon (BC) and nitrogen dioxide (NO_2) is well researched (Hoek et al., 2013). However, exposure contrasts related to traffic emissions are usually poorly represented by PM (Hoek et et al., 2013). Variation in PM10 and PM2.5 (particles smaller than 10 μm or 2.5 μm) between major roads and background locations are smaller than the variations in BC and NO_2 (Boogaard et al., 2011). Ultrafine particulate matter (UFPM) and CO are also suitable indicators for TRAP with high contrasts (Grange et al., 2013; Karner et al., 2010), but the health effects are not yet as well researched as for BC and NO_2. Therefore, BC and NO_2 are used to compare concentrations between on road cycling and bicycle paths away from the carriageway.

Spatial variations of exposure to TRAP result from where the sources (motor vehicles) are concentrated and the recipient’s distance from the sources. Pollutants dilute significantly with distance (see for instance Rijnders et al., 2001). MacNaughton et al. (2014) found lower exposures to TRAP for those on bicycle paths compared with bicycle lanes (24% lower for BC and 25% lower for NO_2). Comparing these circumstances, Hatzopoulou et al. (2013) found a reduction of 12% for BC. We expect that exposure at distributor roads with mixed traffic and with bicycle lanes does not differ because research does not suggest an increased overtaking distance at bicycle lanes as compared with roads with mixed traffic (Parkin and Meyers, 2010; Stewart and McHale, 2014). It could be that other factors related to

TRAP exposure like traffic turbulence are affected by building bicycle lanes but to our knowledge there is no specific research available.

Bicycle paths and lanes will also affect exposure to air pollution by attracting cyclists to distributor roads (an effect on route choice) and reducing the use of low-traffic residential roads where concentrations are lower (Gommers and Bovy, 1987; Jensen, 2006). Several studies compared TRAP in cyclists between low and high volume roads. Jarjour et al. (2013) and Strak et al. (2010) found reductions between 15% and 28% for BC on low volume roads. Jarjour et al. (2013) defined low volumes as less than 4,000 vehicles per day and indicated that many parts of the low-traffic routes in their study were likely to have less than 1,500 vehicles per day. Traffic counts on high-traffic routes in this Californian study ranged between 10,000 and 26,000 vehicles per day. Volumes on low and high volumes roads in the Dutch study by Strak et al. (2010) were in the same range, i.e. low volumes were defined as less than 4,500 vehicles per day and high volumes as between 10,000 and 30,000 vehicles per day. Hatzopoulou et al. (2013) did not explicitly compare high and low-volume roads but they did find a significant BC reduction of 15% if the number of trucks and buses on the nearest traffic lane decreased by 10 per hour. A 12% reduction for NO_2 was found by Hertel et al. (2008) along low volume roads as compared with high volume roads. This Danish study did not define the range used to define high and low volumes. Given the similarities between the Netherlands and Denmark, we expect them to be in the same range as in the Dutch study by Strak et al. (2010).

In summary, the available cycling-specific evidence suggests that the higher the volume of motorised traffic, the greater is cyclists’ exposure to air pollutants. Bicycle paths that offer lateral separation between the cyclist and the motorised traffic reduce cyclists’ exposure to air pollutants.

1.3 Road safety

Bicycle lanes have been found to reduce injury rate and collision frequency compared with roads with mixed traffic (Reynolds et al., 2009). Review studies report injury rate reductions for cycle lanes between 9% and 50% (Elvik et al., 2009; Reynolds et al., 2009). Smaller but positive effects are also reported for bicycle paths provided that effective intersection treatments are employed (Thomas and DeRobertis, 2013). The meta-analysis by Elvik et al. (2009) suggests a 7% increase in the number of bicycle-motor vehicle (BMV) crashes after bicycle paths are installed, but the authors indicated that most of the studies did not control for potentially changed bicycle use on these roads. In their review study Thomas and DeRobertis (2013) indicate that a study by Lusk et al. (2011) best meets their quality criteria such as control for exposure. This study found a 38% reduction of injury and fatal BMV crashes.

Bicycle lanes and paths will also affect road safety by attracting cyclists to the distributor roads where these facilities are applied (Gommers and Bovy, 1987; Jensen, 2006). This change in route choice is important because even after building bicycle paths, cyclists on distributor roads still run a higher risk of collisions than cyclists on residential roads (Liu et al., 1995; Schepers et al., 2013; Teschke et al., 2012). Attracting more cyclists to distributor roads results in more cyclists exposed to the increased risks along distributor roads. Most studies on the safety of urban bicycle lanes and paths in the meta-analysis by Elvik et al. (2009) did not control for the numbers of cyclists after bicycle paths were built. The result of the meta-analysis therefore includes the effect of cyclists diverted to routes along distributor roads with elevated risks. However, it also includes the effect of increased overall volumes of cyclists. Therefore, an estimation based on this meta-analysis is likely to result in rather conservative expectations of the road safety impact of lanes and paths. The study by Lusk et al. (2011) on the other hand did control for exposure. That study is likely to yield rather optimistic estimations because the effect of cyclists’ route choice is excluded. Taken together, the effect percentages from the above mentioned studies provide a realistic range of overall road safety effects of bicycle lanes and paths after accounting for changed route choice.

1.4 Health impact in terms of mortality

This section describes how changes in active transport, inhaled air pollution and involvement in crashes are related to all-cause mortality. Mortality serves as a suitable common metric as its link with all three exposures is well established in scientific literature (De Hartog et al., 2010). Especially for physical activity associated with walking and cycling, the current cycling and walking-specific evidence for morbidity is more limited than that for mortality (Kelly et al., 2014; Oja et al., 2011), which is why it has not yet been included in the World Health Organisation’s (WHO) Health Economic Assessment Tool (HEAT) (Kahlmeier et al., 2013).

1.4.1 Increased physical activity resulting from active transport

Cycling has been recognized as an important means to prevent the risk of sedentary lifestyles and promote health (Fishman et al., 2015; Lopez et al., 2006; Oja et al., 2011). Based on a meta-analysis, the first one focused on cycling, Kelly et al. (2014) suggest a relative mortality risk of 0.90 (95% CI = 0.87 to 0.94) for 100 minutes of cycling per week. This implies that with an increase of 100 minutes cycling per week the risk reduction for all-cause mortality is 10% as compared with non-cyclists. For walking the meta-analysis outcomes indicated a relative risk of 0.89 (95% CI = 0.83 to 0.96) for 168 minutes of walking per week. The 100 and 168 minutes of cycling and walking per week correspond to 11 Metabolic Equivalent of Task (MET) hours (Kelly et al., 2014).

To circumvent the lack of cycling and walking-specific evidence for morbidity, some researchers estimate the morbidity impact using research on moderate physical activity in general (e.g. Woodcock et al., 2013). The amount of cycling and walking are translated into MET hours. The health benefits of MET hours of cycling and walking are assumed to be equal to those of moderate physical activity in general. This approach is valuable for estimating the absolute size of the health impact of an intervention because this requires the inclusion of morbidity. However, this approach is not yet sufficiently reliable to compare the health impact of more time spent cycling to other health impacts like air pollution. A meta-analysis found 11 MET hours of moderate physical activity was associated with a relative risk of 0.81 (95% CI = 0.76 to 0.85) (Woodcock et al., 2011), i.e. an almost two-fold greater reduction of the odds of dying per MET hour than for walking and cycling. This suggests that cycling, and walking specific estimates like the meta-analyses by Kelly et al. (2014), are needed to estimate the health benefits of cycling and walking. These are not yet available for morbidity (Oja et al., 2011).

A dose-response relationship is needed to estimate the health benefits of a given increase of the amount of cycling or walking. WHO (2013) estimated that the differences in model fit between different models was not substantial. However, the general literature on non-vigorous physical activity suggests that the longevity benefits level off at higher levels (Woodcock et al., 2011). Kelly et al. (2014) distinguished three categories and also found the greatest rate of reduction due to cycling for an exposure between 0 and 11.25 MET hours per week, corresponding to a base rate of maximally 100 minutes of cycling.

1.4.2 Inhaled air pollution

A review by Hoek et al. (2013) shows that the relative risk of all-cause mortality for an increase of long term exposure to BC is 1.061 per 1 $\mu g/m^3$ (95% confidence interval [95% CI] = 1.049 to 1.073) and for an increase of NO_2 1.055 per 10 $\mu g/m^3$ (95% CI = 1.031 to 1.080). In traffic, the exposure is not only dependent on the concentration but also on the ventilation rate of road users. Total daily doses of pollutants (the product of ventilation rate, duration of exposure, and concentration) have to be estimated to take the increased respiratory rate in cyclists into account (De Hartog et al., 2010; Int Panis et al., 2010). The change of the inhaled dose of pollutants for a scenario is the basis for estimating an ‘equivalent’ change in concentration to which the relative risks of the Hoek et al. (2013) study would then apply.

1.4.3 Traffic safety

Changes in numbers of fatalities are estimated in road safety research by applying effect percentages to a group of casualties affected by an intervention (e.g. cyclist casualties affected by a new bicycle path). The relative risk of all-cause mortality associated with the intervention is derived using the following equation: (ACM + CF) / ACM (in which ACM stands for the all-cause mortality rate and CF for the change in the number of fatalities due to the intervention (De Hartog et al., 2010).

2. Data and Method

We explored the impact on mortality of bicycle infrastructure associated with increased cycling, and the risks of air pollution and road safety among cyclists. We examined the relative size of these three impacts. We focused on mortality rather than morbidity as a common metric because the effects of the three exposures on mortality are more reliably researched than for morbidity (Kahlmeier et al., 2013). A shift from driving to cycling has additional health benefits, i.e. reduced risk posed to other road users and decreased air pollution emissions and noise (Rydin et al., 2012; Schepers and Heinen, 2013), but these issues are excluded because of their small mortality impact (De Hartog et al., 2010).

2.1 Scenario

We modelled the impact of a scenario with 3.3 km of new bicycle lanes and 3 km of bicycle paths in a hypothetical city having 100,000 inhabitants with the volumes of cycling and levels of air pollution and cycling safety that can be expected in an average Dutch city (average bicycle modal share is 26% to 27% according to Harms et al., 2014 and the Ministry of Transport, Public Works, and Water Management, 2009.). These measures resembled the intervention of new bicycle paths and lanes in the Dutch city of Delft in the 1980s, also a city with some 100,000 inhabitants. Consistent with Delft, we assumed an increase of bicycle lanes and paths of 0.5km/km^2. Expressed as share of the length of the distributor road network, the length of bicycle lanes increases by 4.4%, while the length of bicycle paths increases by 4.0%.

2.2 Data

Data on Dutch volumes of cycling and road safety between 2010 and 2013 were retrieved from Statistics Netherlands and SWOV Institute for Road Safety (Statistics Netherlands, 2015; SWOV, 2015). Average concentrations of relevant air pollutants at background and street locations were used from studies by Keuken and Ten Brink (2010) and Hoogerbrugge et al. (2012).

2.3 Method

Dutch population and hazard rates were entered in the open-access life-table calculations, IOMLIFET, to estimate the gain in life years in response to the reduced risk of mortality per age group (Miller, 2013). We have estimated the effects on this population for a lifetime. As the level of cycling participation among people above 90 years of age is minimal (and therefore the available data is less reliable) we excluded this age group for all impacts. No impact of physical activity was assumed for those under 20 years as the meta-analysis by Kelly et al. (2014) on the impact of physical activity related to cycling included studies with an age range between 20 and 93 years. In line with what is conventional in health impact assessments of air pollution, we assumed no impact of air pollution on mortality among people younger than 30 years of age. Road safety effects were included for all age groups except those above 90 year of age.

The Dutch standard value of a statistical life (VSL) is used to monetise the number of deaths per year prevented by cycling participation (Kahlmeier et al., 2013). The Dutch VSL amounts to €2.8 million per death at the 2013 price level (De Blaeij, 2003; Statistics Netherlands, 2015). We applied the standard 5.5% discount rate and use 30 years as a time horizon, which is prescribed in the Netherlands for cost-benefit analysis of infrastructure projects (Ministry of Finance, 2007; Wesemann and Devillers, 2003).

The Netherlands has high levels of cycling participation and is one of the safest countries in the world for cyclists (Pucher and Buehler, 2008; Schepers et al., 2015). This raises the question of whether the outcomes are transferable to countries with lower volumes of cycling. We will explore the sensitivity of our outcomes for the base level of cycling assuming a two-fold lower baseline bicycle modal share (as compared with the Netherlands) and a level of cycling safety that can be expected in a country with a lower level of cycling.

3. Estimating the health impact

Sections 3.1 up to 3.3 describe how the relative risks of mortality are estimated for our scenario. As depicted in Figure 4, the changed time spent cycling in the scenario directly feeds into an estimation of risk of all-cause mortality (Section 3.1). The estimation of the impact related to air pollution is more complicated. The scenario has a direct impact on the air pollution concentration per road type. Additionally, because of changed route choice (derived from the evaluation of the Delft bicycle network, see Table 1) the time spent per road type changes. Together these two changes affect air pollution exposure and thereby the risk of all-cause mortality (Section 3.2). The same line of reasoning applies to road safety, but the available research does not allow us to explicitly distinguish between effects related to route choice and road safety risks at the location level due to bicycle infrastructure (Section 3.3). Section 3.4 describes the impact on life expectancy. Section 3.5 briefly discusses sensitivity of the calculations. Section 3.6 describes an economic valuation of the benefits and costs to put the benefits in perspective.

3.1 The health impact of cycling related to physical activity

We modelled the impact on bicycle modal share via the density of bicycle lanes and paths. Proximity to bicycle infrastructure would be an alternative to operationalize different degrees of intervention exposure (Goodman et al., 2014; Heinen et al, 2015a&b), but we use density as most published research was based on this exposure measure. The studies by Barnes et al. (2006) and Dill and Carr (2003) suggest between 1.0 and 1.6 percentage points of bicycle modal share per km of bicycle lanes and paths per square kilometre, yielding an estimated increase between 0.5 and 0.8 percentage points of bicycle modal share for our scenario in which the density increased by 0.5km/km^2. Using these figures the following steps are taken to estimate the reduction of the risk of all-cause mortality:

- To relate the change in bicycle modal share to time spent cycling we need to know the relationship between these two variables. We regressed bicycle modal share on the time spent cycling per capita in all 66 Dutch municipalities having a population over 50,000, using the National Travel Survey in 2010-2013 (Statistics Netherlands, 2015). The results of linear regression without a constant suggest that time spent cycling is proportional to bicycle modal share (Beta=0.99, $p<0.001$, $R^2=0.98$). The time spent cycling per capita per week among Dutch people above 20 years is 74 minutes; the bicycle modal share is 26% (Statistics Netherlands 2015), yielding 2.85 minutes per percentage point of bicycle modal share. With these outcomes we can estimate that the bicycle modal share increase between 0.5 and 0.8 percentage points corresponds to between 1.4 and 2.3 minutes per week. This modelling approach assumes the absolute increase of bicycle modal share is independent of the base level of cycling and that the relative increase becomes smaller as the baseline level of cycling increases. Applying a constant relative increase would yield a much greater absolute increase where the baseline level of cycling is already higher (such as in our hypothetical scenario city). We consider this unrealistic for our scenario in the Netherlands as the cycling market is likely to get saturated more quickly given the higher Dutch levels of cycling.
- According to Kelly et al. (2014) 100 minutes of cycling per week reduces the risk of all-cause mortality by 10%, assuming a linear dose-response relationship. With a base level of 74 minutes per week, between 1.4 and 2.3 additional minutes per week yields a risk reduction for all-cause mortality between 1.5 and 2.5 per thousand $(1-(1-0.90) * (\text{min}_{\text{after}} /100)) / (1-(1-0.90) * (\text{min}_{\text{before}} /100))$ (Kahlmeier et al., 2014).
- The aforementioned reduction of all-cause mortality is an overestimation if cycling displaces walking. However, we do not consider reduced levels of walking or other forms of physical activity because such reductions have not been found in evaluation studies of bicycle infrastructure (Goodman et al., 2013; Goodman et al., 2014; Katteler et al., 1987).

The results are not likely to be very different if we would assume a non-linear dose-response relationship. The base level of cycling in the Netherlands is somewhat under 11.5 MET hours. For those at lower base levels of cycling the aforementioned mortality risk reduction is conservative while it is optimistic for those at a higher base levels (Kelly et al., 2015). These differences can be expected to cancel each other out.

3.2 Air pollution

To examine the health impact of exposure to air pollution, a daily inhaled dose was estimated for the current situation and scenario. The change was translated into an equivalent change in BC and NO_2 concentration. The inhaled dose is the product of the concentration, the duration of exposure to this concentration, and the ventilation rate. We defined a range for both ventilation rate and street concentration to examine the impact on all-cause mortality. The following steps were used to obtain the inhaled doses:

- Street concentrations: average street concentrations, 4 $\mu g/m^3$ for BC and 45 $\mu g/m^3$ for NO_2 (Hoogerbrugge et al., 2012; Keuken and Ten Brink, 2010), were proportionally scaled to represent the differences between road types described in the literature (see Section 2.2). We assume cyclists are exposed to these street concentrations while travelling, with the highest concentrations on distributor roads with mixed traffic and bicycle lanes. Pollution exposure during the rest of the day (while not travelling) was assumed to be at the background level of 2.2 $\mu g/m^3$ for BC and 20 $\mu g/m^3$ for NO_2 (Hoogerbrugge et al., 2012; Keuken and Ten Brink, 2010). The background level may be lower indoors (Dons et al., 2011). Choosing a lower level hardly affects the outcomes as the background level is unaffected by the scenario.
- Scaling street concentrations: reductions in the range 12% and 24% for BC and a reduction of 25% for NO_2 (Hatzopoulou et al., 2013; MacNaughton et al., 2014) were used for estimating concentrations on physically separated bicycle paths as compared with bicycle lanes and roads with mixed traffic. Reductions in the range 15% and 28% for BC and 12% for NO_2 (Hatzopoulou et al., 2013; Hertel et al., 2008) were applied to the concentration on low volume roads as compared with high volume roads. The volumes on low and high volume roads in the underlying studies (Hertel et al., 2008; Jarjour et al., 2013; Strak et al., 2010) are comparable to volumes on Dutch access and distrbutor roads respectively. For roads carrying more than 4,000 to 5,000 vehicles per day (the upper level being defined as the upper limit for a low volume road in the aforementioned studies), the Dutch Design Manual for Bicycle Traffic (CROW, 2007) advises building bicycle paths or lanes. The upper level of the effect range for BC was estimated by taking the greatest difference of distributor roads with paths versus lanes (24%) and the smallest difference of low volume roads versus distributor roads (15%).
- Duration of cycling per road type: the duration of time spent cycling was split amongst road types according to the share of kilometres travelled per road type for the intervention in Delft, see Table 1. This accounts for changes in route choice. Table 2 is based on 74 minutes of cycling per week (0.176 h/day), the average of Dutch citizens above 20 years of age (Statistics Netherlands, 2015).
- In accordance with De Hartog et al. (2010) we assumed a ventilation rate of 5 l/min during sleep and 10 l/min during rest while a range between 21 and 50 l/min is assumed for

cycling (Bernmark et al., 2006; Int Panis et al., 2010; van Wijnen et al., 1995; Zuurbier et al., 2009) with 1 l/min equalling 0.03 m^3/h. We applied the highest value for the upper level of the effect range, and vice versa for the lowest.

Table 2 presents the steps in the calculation and outcomes. The effects on mortality are small (indicated by risk reductions for all-cause mortality between 0.00 and 0.06 per thousand). Relative risks of all-mortality based on BC and NO_2 are generally in the same range.

>> Table 2 about here

3.3 Road safety

We used a range of 9% to 50% for bicycle lanes and -7% to 38% for bicycle paths for the reduction of the number of bicycle-motor vehicle crashes on distributor roads (Elvik et al., 2009; Lusk et al., 2011; Reynolds et al., 2009). Effects through route choice are included in this range of effect figures. The following steps were applied to estimate the impact on all-cause mortality:

- In the scenario, the length of distributor roads with bicycle lanes and paths represents 4.4% and 4.0% of the total length of distributor roads respectively. Therefore, the group of fatalities affected by building bicycle lanes and paths was estimated at 4.4% and 4.0% respectively, of the annual number of 58 cyclist fatalities in BMV crashes on distributor roads within urban areas in the Netherlands between 2010 and 2013, i.e. 2.6 and 2.3 cyclist fatalities per year (SWOV, 2015).
- The effect size percentages were applied to the numbers of cyclist fatalities estimated in the previous step:
    - Lower level effect range: reduction of the number of cyclist fatalities by 0.1 (9% x 2.6 - 7% x 2.3)
    - Upper level effect range: reduction of the number of cyclist fatalities by 2.2 (50% x 2.6 + 38% x 2.3)
- This was combined with the current mortality rate to estimate the risk reductions for all-cause mortality using the formula described in Section 2.4.3. The total number of fatalities is 138,000 per year (Statistics Netherlands, 2015). The risk reduction for all-cause mortality is between 0.00 and 0.02 per thousand:
    - Lower level effect range: 1000*(1 - (138,000 – 0.1)/ 138,000
    - Upper level effect range: 1000*(1 - (138,000 – 2.2)/ 138,000

The impact on all-cause mortality is small, even if the largest effect estimates are assumed.

3.4 Life expectancy and comparison of health effects

As a rule of thumb, a 1% reduction of all-cause mortality risk in the adult population increased life expectancy by about 30 days (Miller and Hurley, 2006), i.e. 1 per thousand corresponds to 3 days. For instance for the lower level of the all-cause morality risk reduction due to more time spent cycling of 1.5 per thousand, the expected increase in life expectancy is 4.5 days. The change of the relative risk of mortality is almost proportional to life years (Miller and Hurley, 2006). This suggests that the health impact related to more time spent cycling (primarily due to more physical activity) is dominant in the overall health impact and much larger than the health impact related to road safety and air pollution.

3.5 The sensitivity of the calculation for the base level of cycling

To aquire a more reliable estimate, all of the calculations described in Sections 3.1, 3.2, and 3.3 were repeated per age group with bicycle use, population, and mortality rates of a hypothetical city having 100,000 inhabitants with characteristics of the Dutch population in 2010-2013 (Statistics Netherlands, 2015; SWOV, 2015), see Table 3. Life table calculations were undertaken using the IOMLIFET spreadsheet (Miller, 2013) to estimate the number of life years gained with the mortality risk reductions in Table 3. Even the most conservative estimate for the effect of physical activity on mortality (4.1 life days gained per person) is substantially greater than the most optimistic estimates for reduced exposure to air pollution (0.1 life days gained per person) and road safety (0.1 life days gained per person). The outcomes suggest that a more detailed calculation distinguishing age groups does not change the outcome. The detailed calculation yields a slightly lower life expectancy gain than the rough estimation presented in Section 3.4, e.g. the most conservative estimate for the effect of more time spent cycling was 4.5 life days gained in Section 3.4 versus 4.1 according to the detailed calculation described above.

>> Table 3 about here

Half the base level of cycling was assumed for a sensitivity analysis, i.e. a 13% bicycle modal share and 37 minutes of cycling per person per week. As our modelling approach assumes the absolute increase of bicycle modal share is independent of the base level of cycling, the same applies to the absolute increase of the time spent cycling. In other words, in response to the same amount of new bicycle infrastructure, the same increased time spent cycling is assumed for a jurisdiction with a lower bicycle modal share. Therefore, the outcomes for the health benefits associated with more time spent cycling would be almost similar to those described in Section 4.1. However, the study by Kelly et al. (2014) suggests that the health benefits are larger at lower base levels of cycling. We lack sufficiently reliable dose-response functions to estimate more accurately by how much the health benefits would vary according to the base level of cycling. The mortality impact related to air pollution is proportional to the change of the inhaled dose of pollutants which is proportional to the time spent cycling. Halving the latter is associated with a half as low inhaled dose of pollutants and mortality impact. The road safety impact is proportional to the number of fatalities in BMV crashes on distributor roads. Road safety research suggests that reduced volumes of cycling are associated with a less than proportional decrease of the number of BMV crashes (Elvik, 2009). Jurisdictions with lower volumes of cycling have higher risks of BMV crashes (Van Hout, 2007). This means that the road safety impact is reduced but by less than a factor of two. The results of this brief sensitivity analysis confirm that, also at a lower base level, of cycling, the greatest health benefits are due to physical activity. The benefits of reduced exposure to the risks of air pollution and road safety remain small.

3.6 Estimation of the health economic benefits

The number of deaths prevented per year was estimated for economic appraisal (see Table 4). The annual benefits of more time spent cycling are between €2.2 million and €3.6 million. We took the lowest value of €2.2 million for a conservative estimate. A €2.8 million value of a statistical life, 5.5% discount rate, and 30-year time horizon yield total benefits of €32 million. According to CROW, the standard costs for reconstructing a road with mixed traffic to provide bicycle paths along both sides is around €2 million/km, including all costs such as buying land and reconstructing intersections. Maintenance requires around €4,000 per year (CROW, 2007). About 1% of those investments are needed for bicycle lanes provided that the road does not require widening (CROW, 2001). The total costs of 3 km of bicycle paths and 3.3 km of bicycle lanes can be estimated at an investment of €6.1 million plus €12,000 per year for maintenance, accumulating to a total of €6.3 million within the time horizon (future costs are discounted in the same way as future benefits). This suggests a benefit-cost ratio around 5 based on the health benefits of reduced mortality as a result of more time spent cycling (i.e. every €1 invested in bicycle infrastructure returns about €5 in health benefit). The benefits are likely to be greater if other benefits such as reduced morbidity are included as well.

4. Discussion

4.1 Principal findings

We have estimated the health benefits of bicycle lanes and paths, assuming a scenario with 0.5km/km^2 of new bicycle lanes and paths (about an equal share of both facilities) in a hypothetical Dutch city with a population of 100,000. Modelling the currently available research on mortality related to time spent cycling, air pollution risks and cycling safety, suggested that bicycle lanes and paths are associated with health benefits, primarily due to increased cycling (and consequent physical activity). However, the impact on time spent cycling is also subject to the greatest uncertainty due to a lack of causal evidence. Only few high-quality quasi-experimental research (with a before-after design) is available. Reduced exposure to the risks of air pollution and road safety may have additional health benefits among all cyclists. However, their effect size is relatively small. A lower base level of cycling – under the assumptions of this paper – does not substantially change these conclusions.

4.2 Strength and weaknesses

A major strength of this study is the quantitative comparison of different health aspects associated with bicycle infrastructure. However, the study has a number of weaknesses. The mobility effects are still uncertain. There are only a few high quality before-after studies (Scheepers et al., 2014) and those that are available are mainly from countries with lower base levels of cycling (Barnes et al., 2006; Pucher et al., 2010). We therefore recommend to evaluate a variety of bicycle infrastructure facilities in areas representing a wide range of base levels of cycling participation. This will assist in developing improved estimates of causal relationship between bicycle infrastructure and cycling. Although only true experiments (with random assignment of participants to an experimental and control group) enable testing causal hypotheses, evaluations using a quasi-experimental design can substantially improve internal validity (Heiman, 2002) compared with correlational research. Information about intervention characteristics needed to inform ex-ante evaluations is often lacking and the debate about how to operationalize different degrees of intervention exposure is ongoing (Goodman et al., 2014;

Scheepers et al., 2014). This information is needed to describe dose-response relationships. Increasing the evidence base of the impact of bicycle infrastructure on mobility is most important to improve the quality of health impact assessments. Evaluations should include modal choice, duration, and route choice because these are needed for health impact assessment of bicycle infrastructure.

Our study only included health benefits that concerned cyclists. There are additional benefits for other road users who are less exposed to air pollution and road safety risks, as well as people living along busy roads who are less exposed to air pollution and noise. These impacts are likely to be smaller than the health benefits of increased physical activity due to cycling (De Hartog et al., 2010; Van Kempen et al., 2010), but including them would more accurately estimate the expected total health benefits of bicycle infrastructure.

This study was restricted to mortality because the evidence for mortality is more conclusive than for morbidity (Kahlmeier et al., 2014). This raises the question of whether a health impact assessment including morbidity would yield different results. A commonly used measure for the total disease burden is the number of Disability Adjusted Life Years (DALYs) which combines the years of life lost (mortality) and years of life lived with disability (morbidity) (Polinder et al., 2015). Some 60% of the total number of DALYs related to physical inactivity in the Netherlands has been estimated to result from morbidity (De Hollander et al., 2006). The risks of air pollution are primarily related to cardiovascular and respiratory diseases (Hoek et al., 2013), of which about half of the disease burden results from morbidity (RIVM, 2012). The road safety effects of bicycle lanes and paths is limited to bicycle-motor vehicle crashes (Reynolds et al., 2009; Thomas and DeRobertis, 2013), of which between 50% and 60% of the disease burden is related to morbidity (Dhondt et al., 2013; Polinder et al., 2015; Weijermars et al., 2014). Non-motor vehicle crashes are excluded. These results suggest that it is important to include morbidity to assess the absolute size of the health benefits of bicycle infrastructure. The shares of morbidity in the disease burdens of the three health aspects included in our study do not strongly differ. This means that the relative sizes are unlikely to change if we would include the whole disease burden. However, more research on the morbidity impact of more people cycling, and those who already cycle cycling longer, as well as air pollution risks would be needed to draw firm conclusions.

4.3 Policy implications

This study suggests that, based on currently available research, the health benefits of bicycle infrastructure due to increased time spent cycling are significant. The dominant benefit comes in the form of increased physical activity, with lesser contributions from enhanced road safety and lower air pollution exposure. The outcomes of a health impact assessment of bicycle infrastructure are most sensitive to the effect on time spent cycling but the empirical evidence of this effect is still weak. Evaluation research is therefore paramount. However, transport policy decisions are taken every day, hopefully supported by guidance and/or impact assessments. This warrants an approach based on the best available evidence. Current knowledge suggests that, in order to support decisions that improve public health, design guidelines should be based on a more integral approach including not only road safety, but also effects on bicycle use and air pollution exposure. Obviously, decisions about new bicycle infrastructure should also account for practical realities like available space and the speed at which a complete bicycle network can be achieved.

4.4 Summary and conclusions

Based on currently available research, we conclude that the introduction of bicycle paths and lanes is likely to be associated with health benefits, primarily due to increased physical activity. However a firm conclusion can only be reached if stronger causal evidence becomes available on the mobility effects of bicycle infrastructure.

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