Health impact assessment of cycling network expansions in European cities

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ABBREVIATIONS

CI	confidence interval
EPOMM	European Platform on Mobility Management
ERF	exposure response function
GADM	Database of Global Administrative Areas
HIA	health impact assessment
MET	metabolic equivalent of task
OSM	OpenStreetMap
PA	physical activity
PAF	population attributable fraction
PASTA	Physical Activity through Sustainable Transport Approaches
$PM_{2.5}$	particulate matter with a diameter of $\leq$2.5 µg/m^3
RR	relative risk
S	scenario
SD	standard deviation
TEMS	European Platform on Mobility Management Modal Split Tool
VoSL	value of statistical life
WHO	World Health Organization

ABSTRACT

Introduction: We conducted a health impact assessment (HIA) of cycling network expansions in seven European cities. We modeled the association between cycling network length (km) and cycling mode share (%) and estimated health impacts of the expansion of cycling networks.

Methods: We performed a non-linear least square regression to assess the relationship between cycling network length and cycling mode share for 167 European cities. We performed a quantitative HIA for the seven cities of different scenarios (S) assessing how an expansion of the cycling network (i.e. 10% (S1); 50% (S2); 100% (S3), and All-streets (S4)) would lead to an increase in cycling mode share and estimated mortality impacts thereof. We quantified mortality impacts for changes in physical activity, air pollution and traffic incidents. We also conducted a cost-benefit analysis.

Results: The length of the cycling network was associated with a cycling mode share of up to 24.7% in European cities. The All-streets scenario (S4) produced greatest health benefits through increases in cycling for London with 633 premature deaths (95% CI: 262 to 1004) avoided annually, followed by Rome (225; 95% CI: 90 to 360), Barcelona (124; 95% CI: 55 to 192), Vienna (81; 95% CI: 32 to 131), Zurich (27; 95% CI: 11 to 43) and Antwerp (4; 95% CI: 1 to 6). The largest cost-benefit ratios were found for the 10% increase in cycling network (S1).

Conclusions: In European cities, expansions of cycling networks were associated with increases in cycling and estimated to provide health and economic benefits.

KEYWORDS: cost-benefit analysis; cycling network; health impact assessment; mode share; mortality; open data

1. INTRODUCTION

There is increasing awareness of the adverse effects of the car-centric urban mobility plans of previous decades (Nieuwenhuijsen and Khreis, 2016). Concerns are sustained on ecological issues such as high levels of pollution, greenhouse gas emissions, the loss of natural outdoor environments and their eco-systems their eco systems, but also on economic issues of space scarcity, congestion costs and financing infrastructure (Khreis et al., 2016; Marqués et al., 2015).

Recently, also the adverse effects on health of our automobile lifestyles have been recognized more holistically (Nieuwenhuijsen and Khreis, 2016) and were estimated to account for a considerable burden of disease (Briggs et al., 2016; Mueller et al., 2017; Tainio, 2015). Not only the risk of traffic incidents, but also other health consequences associated with car-centric transport planning are increasingly considered, such as impacts on physical activity (PA) levels or exposure to air pollution and noise (Götschi et al., 2015; Mueller et al., 2017; Rabl and de Nazelle, 2012).

Promoting a mode shift to cycling for transport has been proposed as a promising strategy in urban environments to overcome aforementioned these issues (Mueller et al., 2015). Cycling for transport can substantially increase total physical activity (PA) levels (Foley et al., 2015; Goodman et al., 2014; Sahlqvist et al., 2013), and is a non-emitting mode of transport. However, to facilitate a shift to cycling, well-designed and safe infrastructure to accommodate cycling is needed (Mertens et al., 2016a; Pucher et al., 2010).

Recent research evidence indicates positive associations between cycling network length and cycling mode share (Buehler and Dill, 2016; Habib et al., 2014; Marqués et al., 2015; Schoner and Levinson, 2014; Schoner et al., 2015). Thus, expansions of cycling networks may increase cycling for transport, which in return may contribute to improvements in public health. However, until now the exposure response relationship between cycling network and cycling mode share in European cities is unknown. Therefore, we assessed (1) the association between cycling network length (km) and cycling mode share (%) and (2) how an increase in cycling mode share might alter expected mortality in terms of changes in PA ~~performance, exposure to,~~ air pollution and ~~the risk of~~ traffic incidents. We also estimated the cost-benefit trade-off between cycling network expansions and economic benefits from avoided premature mortality.

2. METHODS

2.1 Association between cycling network and cycling mode share

2.1.1 Non-linear least square regression

Data preparations steps are documented (Salmon and Mueller, 2017). We obtained data on population size, cycling mode share and cycling network length for 167 cities located in 11 European countries (4 Austria, 7 Belgium, 2 Denmark, 20 France, 47 Germany, 15 Italy, 23 Netherlands, 14 Spain, 9 Sweden, 2 Switzerland, 24 United Kingdom) (**Table A.1**). Amongst the 167 cities were the seven case study cities of the Physical Activity ~~t~~Through Sustainable Transport Approaches (PASTA) project (i.e. Antwerp, Barcelona, London, Rome, Örebro, Vienna, Zurich) (**Fig. 1**) (Gerike et al., 2016). The other 160 cities were chosen based on (1) their geographic representativeness of Northern, Central and Southern Europe, (2) population size

≥100,000 persons, (3) the availability of mode share data not being older than 2006 and (4) the availability of spatial boundaries.

Data on cycling mode share and population size were obtained through the European Platform on Mobility Management (EPOMM) Modal Split Tool (TEMS) (EPOMM, 2011). ~~Official S~~spatial administrative municipality boundaries were obtained from the Database of Global Administrative Areas (GADM) (Hijmans, 2009), the UK data service (Office for National Statistics, 2011), and the Swedish lantmäteriet (Swedish Ministry of Enterprise and Innovation., 2016). We used OpenStreetMap (OSM) to compute cycling network lengths for all 167 cities (**Table 1**) using labels of designated, non-shared cycling ways (**Table A.2**) (OpenStreetMap contributors, 2017). We also computed the street network ~~distance~~ length (km) for the ~~seven~~ PASTA cities.

Analyses were conducted in R (version 3.1.1) and Microsoft Excel. ~~Used Rpackages were: dplyr (Wickham and Francois, 2016), geosphere (Hijmans, 2016a), ggflags (Auguie, n.d.), ggmap (Kahle and Wickham, 2013), ggplot2 (Wickham, 2009), ggrepel (Slowikowski, 2016), ggsn (Santos Baquero, 2016), htmltools (RStudio and Inc., 2016), htmlwidgets (Vaidyanathan et al., 2016), httr (Wickham, 2016a), leaflet (Cheng and Xie, 2016), lubridate (Grolemund and Wickham, 2011), maptools (Bivand and Lewin-Koh, 2016), nlstools (Baty et al., 2015), overpass (Rudis and Lovelace, n.d.), purr (Wickham, 2016b), raster (Hijmans, 2016b), readr (Wickham et al., 2016b), readxl (Wickham, n.d.), rgdal (Bivand et al., 2016), rgeos (Bivand and Rundel, 2016), sp (Pebesma and Bivand, 2005), tibble (Wickham et al., 2016a), and viridis (Garnier, 2016).~~

We standardized the computed cycling network length of the 167 cities by population size. We used 'cycling network km/ 100,000 persons' as the explanatory variable and performed a non-linear least square regression (i.e. Gompertz growth model) to calculate the corresponding cycling mode share (%) with $y(t) = ae^{-be^{-ct}}$, where a is the asymptote (i.e. maximal cycling mode share associated with cycling network), b sets the displacement along the x-axis and c sets the displacement along the y-axis (i.e. growth rate), t is the cycling network km/ 100,000 persons. ~~Our reasoning for choosing this growth model compromising an asymptote are that it best describes our dataset and us~~ We assumed ~~assuming~~ that the explanatory properties of cycling network being associated with cycling mode share are non-linear and limited. We added ~~basic~~ bootstrap confidence intervals (CIs) based on the empirical 0.025-quantile and 0.975-quantile of the distribution resulting from 1,000 bootstrap samples.

2.2 Health impact assessment

~~To address our second objective of assessing how an increase in cycling mode share would impact public health~~ Wwe ~~carried out~~performed a ~~quantitative~~ health impact assessment (HIA) for the ~~seven~~ PASTA cities to estimate how an increase in cycling would impact public health ~~(i.e. Antwerp, Barcelona, London, Örebro, Rome, Vienna, Zurich)~~. Baseline demographic, transport and mortality data were available through the PASTA project (Dons et al., 2015; Gerike et al., 2016).

2.2.1 Scenarios

Across different scenarios (S), we assessed how the cycling mode share would change with an increase in the cycling network length by 10% (S1); 50% (S2); 100% (S3); and

~~how the cycling mode share would change~~ if all streets (km/ 100,000 persons) of the city provided designated cycling infrastructure (S4 – All-streets).

2.2.2 Health impact assessment model

The ~~increase in cycling share and the resulting~~ new cycling trips were assumed to be shifted from previous car (25%) and public transport (75%) trips (Rojas-Rueda et al., 2016)~~.~~. ~~We assumed the new cycling trip~~ to have a distance of 5 km and being traveled at a speed of 13 km/h [~~, as w~~we considered this distance not exceeding the willingness to cycle at a speed requesting a light effort (Ainsworth et al., 2011; Rabl and de Nazelle, 2012)]. The walking share was assumed to stay constant. ~~Across the scenarios, W~~we estimated the impact on all-cause mortality due to changes in PA ~~levels~~, ~~exposure to~~ air pollution exposure for the cyclist and the risk for~~of a~~ fatal traffic incidents. Baseline data on all-cause mortality and exposures levels were collected for all seven cities (**Tables A.3-A.13**). 95% CIs for the overall impact were based on the pooled standard deviation (SD) of PA, air pollution and fatal traffic incidents. We assumed the mortality risk to be normally distributed. ~~As we estimated the risk for traffic fatalities directly based on km travelled, we based the 95% CI for expected traffic fatalities on the SD of PA because it was larger than the SD of air pollution and is thus more conservative.~~

2.2.2.1 Physical activity

~~We estimated the impact on mortality due to changes in PA levels resulting of increased cycling.~~ Metabolic equivalents of task (METs) were used as a measure of energy expenditure during PA (**Tables A.4-A.10**). We calculated the gain in METs resulting from substituting car and public transport trips with cycling. A public transport trip was assumed to include a 10 minute walk to/ from public transport (Rojas-Rueda et al., 2012)~~.~~~~, therefore we considered a 10 minute reduction of PA for each substituted public transport trip.~~

We assigned the new bicycle trip ~~the speed of 13 km/h with an energy expenditure of~~ 6.8 METs (Ainsworth et al., 2011; WHO. Regional Office for Europe, 2014a). The replaced 10 minute walk~~ing trip~~ to public transport was assigned ~~the energy expenditure of~~ 3.3 METs (Ainsworth et al., 2011). We calculated the difference in METs between current and gained PA for substituting motorized~~car and public~~ transport trips with the bicycle.

The association between PA and mortality was quantified using a curvilinear exposure response function (ERF) (Relative Risk (RR) = 0.81; 95% CI: 0.76 to 0.85 per 11 MET-hr/week), applying a 0.25 power transformation (Woodcock et al., 2011). We calculated the RR and the population attributable fraction (PAF) for both baseline PA and gained PA. The estimated preventable deaths for current PA were subtracted from estimated preventable deaths for the additional PA.

2.2.2.2 Air pollution exposure cyclist

Particulate matter (PM) with a diameter of ≤ 2.5 $\mu g/m^3$ ($PM_{2.5}$) is a commonly used proxy for air pollution ~~coming~~ from fossil fuel combustion sources (i.e. motorized transport) (**Table A.11**) (Mueller et al., 2015). We considered the altered ~~personal~~ air pollution exposure for the person shifting from car or public transport (including a 10 minute walk) to cycling. ~~Due to immediate traffic proximity, the~~ $PM_{2.5}$ concentration to which car drivers~~, and~~ public transport users, pedestrians and cyclists are exposed to w~~h~~ere~~as~~ set 2.5~~, and~~ 1.9, 1.9 and 2.0 times higher, respectively, than ~~the reported~~ background concentrations (**Table A.12**) (de Nazelle et al., 2017). ~~Also pedestrians and cyclists were assumed to have 1.9 and 2.0 times higher PM~~$_{2.5}$ ~~exposure, respectively,~~

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~~than background levels due to traffic proximity (de Nazelle et al., 2017).~~ Ventilation rates for different leisure and transport activities were available from previous assessments (Rojas-Rueda et al., 2016, 2012). We calculated the daily inhaled $PM_{2.5}$ dose ($\mu g/m^3$/24-hr) stratified by activity and the total dose ($\mu g/m^3$/24-hr) stratified by transport mode. ~~For each scenario, W~~we calculated the equivalent $PM_{2.5}$ dose difference between cycling and motorized transport ~~(i.e. car or public transport)~~ (de Hartog et al., 2010). We used a linear ERF (RR=1.07; 95% CI: 1.04 to 1.09 per 10 $\mu g/m^3$ $PM_{2.5}$ annual mean) to quantify the association between $PM_{2.5}$ exposure and mortality (WHO. Regional Office for Europe, 2014b). We ~~and~~ calculated the corresponding RR and PAF.

2.2.2.3 Traffic incidents

Traffic fatalities were estimated based on injury records and distance traveled. ~~Across the scenarios, f~~For each ~~transport mode~~transport mode the risk ~~for~~ ~~of having~~ a fatal traffic incident per billion kilometers traveled was estimated using the reported annual average number of fatalities and ~~the annual average~~ kilometers traveled ~~for each mode of transport in each city~~ (**Table A.13**). We calculated the RR ~~for~~of a fatal incident for a 5 km cycling trip and compared this risk ~~compared~~ to a car and public transport trip (including a 10 minute walk) of the same distance.

2.2.2.4 Sensitivity analyses

As sensitivity analyses, we ~~estimated health impacts~~ assum~~ing~~ed the new cycling trips to be shifted by 75% from ~~previous~~ car ~~trips~~ and by 25% from ~~previous~~ public transport trips. We also applied a safety-in-numbers effect ~~assuming~~ (i.e. a less than proportional increase in traffic incidents with increases in cycling)~~traffic volume~~ using the summary coefficient of 0.43 for cycle volume ~~of a recent meta-analysis~~ (Elvik and Bjørnskau,

2017). Finally, we performed a HIA for all 167 cities ~~of our analysis~~, supposing achievement of the maximal cycling mode share predicted by our model (i.e. 24.7%). For model inputs, we used the mean of the PASTA city data for transport, exposures and mortality.

2.3 Cost-benefit analysis

We ~~conducted a cost-benefit analysis estimating~~estimated ~~the~~ potential economic costs of ~~expanding the~~ cycling network expansions and compar~~ing~~ed them to ~~the~~ estimated economic benefits of avoided premature mortality. Following the example of the Netherlands, where cycling infrastructure is commonly well-developed, we assumed that each ~~additional~~ 1 km of cycling infrastructure would ~~come at a~~ cost ~~of~~ €2 million, which were estimated costs for reconstructing a road with mixed traffic ~~including buying land and reconstructing intersections~~ (Schepers et al., 2015). An additional € 4,000 per km/ year were considered for maintenance purposes (Schepers et al., 2015). We ~~also~~ considered a 5-year buildup of health benefits and a discounting rate ~~of health benefits~~ of 5% ~~as benefits in the future are less valuable than if they occurred immediately~~ (WHO. Regional Office for Europe, 2014a). We applied a time horizon of 30 years (Schepers et al., 2015), as ~~a~~ strategic transport planning ~~typically plans for 20-40 years ~~into the future~~ahead (Litman, 2014)~~.~~, and benefits of active transport are long-term in nature (Mueller et al., 2015).

We monetized ~~expected~~ health benefits by applying ~~the~~ country-specific value of statistical life (VoSL) estimates ~~d at country level~~ (i.e. ranging between 3,202,968 €for Spain and 7,236,492 € for Switzerland) (**Table A.14**) (WHO. Regional Office for Europe, 2014a). No de-congestion or other benefits were monetized.

3. RESULTS

3.1 Association between cycling network distance and cycling mode share

The non-linear association between cycling network size and cycling mode share in 167 European cities is described in **Fig. 2**. According to our model and dataset, a cycling network of 315 km/ 100,000 persons was associated with a maximal cycling mode share of 24.7% (99.9% of asymptotic value).

Regarding the ~~seven~~ PASTA cities, Örebro and Antwerp showed to have the largest standardized cycling network length (i.e. 260 and 95 km/ 100,000 persons, respectively) followed by Vienna, Zurich, London, Barcelona and Rome (**Table 1**). Likewise, Örebro and Antwerp ~~reported~~ had the largest cycling mode share at baseline (25% and 23%, respectively) followed by Vienna, Zurich, London, Barcelona and Rome (**Table 2**).

According to our model, the PASTA cities, except Örebro and Antwerp, had great potential to increase their cycling mode share through ~~expansions of the~~ cycling network expansions, even though growth rates were expected to vary depending on baseline cycling network length and corresponding mode share. Because our model caps the ~~assumes that expansions of the cycling network are associated with a~~ cycling mode share at~~of up to~~ 24.7%, no increases in cycling was expected for Örebro as at baseline already 25% of all trips were carried out cycling. Also in Antwerp where already 23% of all trips were done cycling, the cycling network length would need to be doubled to achieve a 1% increase in cycling mode share (**Table 3**).

3.2 Estimated health impacts

The PASTA cities were estimated to benefit from an increase in cycling ~~as a result of increases in cycling network length~~, except for Örebro, and Antwerp benefiting only to a small extent (**Table 4**). The All-streets scenario (S4) produced the greatest health benefits through increases in cycling for London with 633 premature deaths (95% CI: 262 to 1004) avoided each year, followed by Rome (225; 95% CI: 90 to 360), Barcelona (124; 95% CI: 55 to 192), Vienna (81; 95% CI: 32 to 131), Zurich (27; 95% CI: 11 to 43) and Antwerp (4; 95% CI: 1 to 6).

In standardized terms, and throughout the proportional increases in cycling network length~~distance~~ (S1 to S3), Vienna and Zurich reaped most benefits (annually 1 to 3 premature deaths/ 100,000 persons avoided). In the All-streets (S4) scenario (absolute increase) and in standardized terms, Barcelona, Rome and London reaped most benefits (annually 7 to 8 premature deaths/ 100,000 persons avoided). Already small increases in cycling network length (i.e. S1; 10%) provided substantial health benefits ~~to health~~ with Vienna benefiting the most in absolute terms with 17 premature deaths (95% CI: 7 to 28) avoided each year, followed by Rome (11; 95% CI: 4 to 18), London (9; 95% CI: 4 to 15), Barcelona (8; 95% CI: 3 to 12) and Zurich (4; 95% CI: 2 to 7).

Throughout the scenarios, benefits were due to increases in PA ~~levels~~ that outweighed ~~associated~~ detriments of air pollution ~~exposure~~ and traffic incidents. The increase in ~~Across the cities, the mode shift to~~ cycling provided greater risks in terms of air pollution exposure than the expected increase in fatal traffic incidents.

The sensitivity analysis assuming the new cycling trips being shifted by 75% from ~~previous~~ car ~~trips~~ and by 25% from ~~previous~~ public transport trips, showed even greater

benefits <u>for all cities</u> ~~with the All-streets scenario (S4) resulting in 724 premature deaths (95% CI: 228 to 1161) avoided in London, followed by Rome (243; 95% CI: 92 to 395), Barcelona (138; 95% CI: 60 to 216), Vienna (92; 95% CI: 34 to 150), Zurich (30; 95% CI: 12 to 48) and Antwerp (4; 95% CI: 1 to 6)~~ (**Table A.15**). Also the safety-in-numbers effect provided additional health benefits ~~with 665 premature deaths (95% CI: 294 to 1036) avoided in London for All-streets (S4), followed by Rome (232; 95% CI: 97 to 366), Barcelona (128; 95% CI: 59 to 197), Vienna (83; 95% CI: 33 to 133), Zurich (28; 95% CI: 12 to 44) and Antwerp (4; 95% CI: 1 to 6)~~ (**Table A.16**).

The HIA for all 167 European cities, with a total population of 75.2 million people, achieving a cycling mode share of 24.7% resulted in 14,500 premature deaths (95% CI: 5,316 to 23,684) avoided ~~each year~~<u>annually</u> (**Tables A.17-A.19**).

3.3 Estimated cost-benefit impacts

The cost-benefit analysis showed generally positive cost-benefit trade-offs, except for Örebro and Antwerp where no or only small health benefits were expected. The largest cost-benefit ratios were found for the 10% increase in cycling network (S1) (Rome € 37:1; Zurich € 28:1; Barcelona € 18:1 Vienna € 13:1; London € 4:1) due to the non-linearity of the cycling network-cycling mode share ~~exposure response relationship~~<u>ERF</u> (**Table A.20**). ~~In the All-street (S4) scenario, cost-benefit ratios were smaller due to the large amount of additional cycling infrastructure required and the time horizon of 30 years almost not being enough time to compensate for the implied costs.~~

4. DISCUSSION

European data on cycling network length and mode share suggest that ~~the availability of~~ a designated cycling network is associated with a cycling mode share of up to 24.7%. We estimated that a large number of premature deaths (i.e. 1,094) could be prevented ~~each year~~annually in six of the seven PASTA cities if the cycling network was the same as the city's street network ~~(km/ 100,000 persons)~~. However, already with a 10% expansion of the cycling network, a considerable number of premature deaths (i.e. 49) could be avoided ~~each year~~annually in five of the seven PASTA cities, which also showed to be the most cost-effective scenario. ~~outweighing estimated costs by 4 to 37 times.~~ If all 167 European cities achieved a cycling mode share of 24.7% 14,500 premature deaths could be avoided ~~each year.~~annually.

To our knowledge, this is the first ~~and largest~~ study evaluating the associations between cycling network length~~size~~, ~~cycling~~ mode share and associated health impacts across European cities. We found the length of the cycling network to be associated with cycling mode share, which coincides with previous research findings (Buehler and Dill, 2016; Buehler and Pucher, 2012; Heesch et al., 2015; Panter et al., 2016). We also estimated ~~an~~ increases in cycling to result in net health benefits, which ~~is~~ also agrees ~~in line~~ with previous research findings (de Hartog et al., 2010; Mueller et al., 2015; Rojas-Rueda et al., 2016, 2013; Woodcock et al., 2014).

A recent World Health Organization (WHO) study estimated almost 10,000 deaths avoidable each year in over 50 European cities under the assumption that the cycling mode share of Copenhagen (i.e. 26%) was achieved (WHO. Regional Office for Europe, 2014c). Our analysis for all 167 cities achieving the estimated maximal mode share of

24.7% attributable to the cycling network, resulted in 14,500 deaths avoidable ~~each year~~annually and is thus comparable to the WHO estimation~~.~~, ~~suggesting that cycling does provide considerable health benefits and should be facilitated.~~

The benefits of ~~increases in~~ PA were estimated to outweigh detrimental effects of air pollution ~~exposure~~ and ~~the risk of~~ traffic incidents ~~across the PASTA cities~~ and therefore net benefits of cycling are independent of geographical context (Mueller et al., 2015; Tainio et al., 2015). In contrast to some studies (Buekers et al., 2015; Dhondt et al., 2013; Rabl and de Nazelle, 2012; Woodcock et al., 2014), but in agreement with other~~s studies~~ (Rojas-Rueda et al., 2012, 2011), we found air pollution exposure for the cyclist to be a greater mortality risk than having a fatal traffic incident. This is due~~can be explained by~~ to our ~~implied~~ modeling assumptions:~~.~~ ~~First~~(1)~~,~~ cycling a distance of 5 km implies a longer exposure duration than traveling the same distance by motorized ~~car or public~~ transport, because of varying speeds;~~.~~ ~~Second,~~(2) a cyclist has a higher ventilation rate ~~-~~due to the implied physical strain. Thus, a cyclist experiences a higher uptake of pollutants for a longer duration; (3)~~. Moreover,~~ we assumed a public transport trip to include a 10 minute walk~~ to/ from public transport~~. Across all ~~seven~~ PASTA cities, walking was the most hazardous mode of transport concerning~~in terms of~~ traffic safety (**Table A.13**). Hence, the assumption that 75% of the new cycling trips substitute previous public transport trips, also shifts the risk ~~of having~~for a fatal traffic incident~~s~~. The reduced risk ~~of having~~for a fatal traffic incident while walking to~~/from~~ public transport makes the estimated increased risk ~~of having a fatal traffic incident~~ while cycling appear less severe.

Örebro and Antwerp, which currently have a larger standardized cycling network, likewise have a higher cycling mode share. As the length of the cycling network was associated with a cycling mode share of up to 24.7%, for Örebro and Antwerp no or only small increases in cycling mode share due to increases in cycling network are expected, which in return results in no or only small health benefits. However, if the true association between cycling network length and cycling mode share was better represented by the 0.975-quantile of the distribution of the 1,000 bootstrap samples (i.e. upper CI), then also in Örebro and Antwerp could expect larger health benefits could be expected. Nonetheless, in Örebro and Antwerp, potentially other policies should be prioritized to further promote increase the cycling mode share. Vienna and Zurich, on the other hand, have great potential to benefit from proportional increases in cycling network distance length due to the fact thatbecause they are at the steeper slope of the growth curve (**Fig. 2**). Thus, and thus their cycling mode share are expected to beis more sensitive to expansions ofin the cycling network in terms of increases in cycling mode share (**Table 3**).

London, Rome and Barcelona are expected to benefit most in absolute and in standardized terms in the All-streets (S4) scenario. T:hese three cities: (1) these three cities have the largerst populations; (2) since the All-streets scenario implies an absolute increase in the cycling network length, London, Rome and Barcelona benefit particularly from the large absolute increase in the cycling mode share (i.e. from 3%, 1% and 2% at baseline, respectively (**Table 3**); and (3) the three cities greatly benefit greatly from the estimated large increases in PA levels [i.e. PA levels were lowest at baseline (**Tables A.4-A.10**)]., yet face health losses due to increased air pollution

exposure (especially Rome) and increased fatal traffic incidents (especially Barcelona and London).

Generally speaking, the cities baseline levels of PA, air pollution levels and traffic fatalities impact benefit estimations significantly (Rojas-Rueda et al., 2016). Health benefits will be largest if at baseline the population is less physically active, air pollution levels are lower and traffic fatalities occur less. Moreover, as demonstratedseen in the sensitivity analysis, the greatest health benefits occur by getting people out of their own cars instead of out of public transport, because public transport provides some hhealth benefits through implied PA (i.e. 10 minute walk) (Rojas-Rueda et al., 2012), and by being the safest mode of transport (Mueller et al., 2015).

PracticalP policy- implications of our findings may be – also under the consideration of the supportive literature – that expansions of cycling networks may increase the cycling mode share, therefore, contributing to global health promotion and meeting sustainable development goals (United Nations, 2015)(Sachs et al., 2016). Designated cycling infrastructure has been identified as one of the most important environmental factors for preferring cycling for transport (de Geus et al., 2008; Heesch et al., 2015; Mertens et al., 2016a, 2016b). While other research also provides insight on 'where' cycling infrastructure should be prioritized (e.g. the propensity to cycle tool) (Lovelace et al., 2016), we would like to emphasize 'that' expansions of cycling networks should be high up on the agendas of city governments which have direct local accountability for

providing 'healthy choices' to their citizens. Especially in cities with a currently low cycling mode share (i.e. Rome, Barcelona, London, Zurich and Vienna), already a 10% increase in cycling network length, which we perceive as a realistic and achievable policy for city governments, was estimated to provide considerable health and economic benefits. and also shows to be most cost effective. Nevertheless, the objective should be maximizing benefits for citizens, thus further expansions of a well-designed cycling network within the ranges of positive cost-benefit trade-offs are justifiable. Despite cost-benefit ratios being smaller, with the All-streets scenario we demonstrate that with ambitious expansions of the cycling network, health benefits will most likely be the largest.

4.1 Limitations and strengths

Notwithstanding, our study has limitations. Other built-environment, transport and socio-economic factors that were shown to influence cycling mode share [e.g. mixed land-use, street density and connectivity, gasoline prices, traffic safety, students among the population, urban greenery, etc. (Beenackers et al., 2012; Buehler and Pucher, 2012; Heesch et al., 2015; Sallis et al., 2015)] were not considered, as data on these parameters were not available, however, Mixed land-use design, street density and connectivity (Beenackers et al., 2012; Cervero et al., 2009; Sallis et al., 2015), car-ownership, individual's mode choice behavior, proportion of students among the population, urban sprawl, gasoline prices and traffic safety (Buehler and Pucher, 2012; Habib et al., 2014; Vandenbulcke et al., 2011), as well as urban greenery (Heesch et al., 2015; Sallis et al., 2015) have all been associated with cycling mode share. All of these factors were ignored in the current univariate analysis, but are expected to alter variability in cycling mode share considerably.

Moreover, as the ~~design of this study~~study design is ecological because ~~because~~ no longitudinal data on cycling network length and ~~cycling~~ mode share were available~~-~~, ~~-~~ no conclusions on causal inferences can be drawn. In fact, ~~This also implies that~~ reversed-causality (i.e. a high cycling mode share leading to reinforcements of the cycling network) cannot be ruled-out. Thus, our results need to be interpreted with caution. ~~In addition, we may have introduced bias by using cycling network data from 2016 but mode share data from 2006 and newer.~~

As with most HIAs, our analyses were limited by data availability and assumptions on causal inferences. Benefit estimations are sensitive to the contextual setting and underlying population and exposure parameters. As no specific exposure parameters were available for the 167 cities (except of the ~~seven~~ PASTA cities) the robustness of the estimated ~~almost 16,000~~14,500 preventable deaths needs to be questioned. City-specific variations in PA, air pollution and traffic incidents will impact the estimations considerably (Tainio et al., 2015). The estimated mortality impacts for the ~~seven~~ PASTA cities considered exclusively the impacts for the actively traveling person, however, further societal co-benefits of reduced air and noise pollution (Buekers et al., 2015; Mueller et al., 2016), reduced greenhouse gas emissions (Woodcock et al., 2009), and improved social cohesion and mental health (Litman, 2016a, 2016b) are expected with reductions in motorized traffic and increases in active transport. Also, quality of life or morbidity impacts have not been considered, but are expected to be considerable. ~~Active transport has been suggested as a measure to improve the total urban environment (Rojas Rueda et al., 2016).~~ In addition, we did not stratify our impact estimations by age, sex, or socio-economic status even though health benefit variations

thereof are expected (Mueller et al., 2015). Finally, the here presented cost-benefit estimations should be regarded as a robust overall estimate of which investments in infrastructure will be offset by health benefits in the long-term. The chosen cost estimates from the Netherlands, despite comprehensively considering reconstruction of roads for mixed traffic, may overestimate ~~implied~~ costs in other settings.

~~For instance, new cycling infrastructure that was built in Antwerp came at a lower costs than assumed in the current study (Buekers et al., 2015).~~

Strengths of this analysis include the novelty of being the first study to look ~~comprehensively~~ holistically into the association between cycling network, cycling mode share and associated health impacts across ~~Northern, Central and Southern~~ European cities. Using open-access OSM data, which for cycling infrastructure has been described of fairly good quality (Hochmair et al., 2013), and applying the same standardized data extraction method across all cities (Salmon and Mueller, 2017) add strength to the study and ensures reproducibility. ~~We intentionally decided not to rely on city level aggregated data that will most likely vary in definitions of designated cycling ways (Buehler and Pucher, 2012).~~

~~Despite the regression analysis being rather simplistic in its design, we believe that nevertheless, interesting insights into the association between cycling network and cycling mode share in European cities are provided. Finally, we encourage further research efforts on the association between cycling network and cycling mode share and associated health impacts thereof to overcome the currently implied uncertainties.~~

5. CONCLUSIONS

Expansions of cycling networks were associated with increases in cycling ~~in European cities.~~ ~~mode share, particularly in European cities with low cycling mode shares. Cities with already high cycling mode shares should consider other policy measures to further increase their cycling mode share.~~ Increases in cycling ~~mode share~~ were estimated to provide considerable health benefits ~~in European cities~~, resulting~~as a result~~ of increases in PA ~~levels~~ ~~that were estimated to outweigh~~that outweighed ~~associated~~ detrimental effects of air pollution ~~exposure~~ and~~or the risk of~~ traffic incidents.

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