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Health impact assessment of cycling network expansions in European cities

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ABSTRACT

We conducted a health impact assessment (HIA) of cycling network expansions in seven European cities. We modeled the association between cycling network length and cycling mode share and estimated health impacts of the expansion of cycling networks. First, we performed a non-linear least square regression to assess the relationship between cycling network length and cycling mode share for 167 European cities. Second, we conducted 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. Third, we conducted a cost–benefit analysis. The cycling network length was associated with a cycling mode share of up to 24.7% in European cities. The all-streets scenario (S4) produced greatest benefits through increases in cycling for London with 1210 premature deaths (95% CI: 447–1972) avoidable annually, followed by Rome (433; 95% CI: 170–695), Barcelona (248; 95% CI: 86–410), Vienna (146; 95% CI: 40–252), Zurich (58; 95% CI: 16–100) and Antwerp (7; 95% CI: 3–11). The largest cost–benefit ratios were found for the 10% increase in cycling networks (S1). If all 167 European cities achieved a cycling mode share of 24.7% over 10,000 premature deaths could be avoided annually. In European cities, expansions of cycling networks were associated with increases in cycling and estimated to provide health and economic benefits.

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 $\leq 2.5\,\mu g/m^3$; RR, relative risk; S, scenario; SD, standard deviation; TEMS, European Platform on Mobility Management Modal Split Tool; VoSL, value of statistical life.

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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 relate to contemporary sedentarism, ecological issues of air and noise pollution, greenhouse gas emissions and the loss of natural outdoor environments, but also to economic issues of space scarcity, congestion costs and financing infrastructure (Khreis et al., 2016; Marqués et al., 2015). Promoting a mode shift to cycling for transport has been proposed as a promising strategy in urban environments to overcome these issues (Mueller et al., 2015). Cycling can 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 is needed (Mertens et al., 2016a; Pucher et al., 2010).

Recent research evidence indicates positive associations between cycling network length and cycling mode share (i.e. percentage of all trips done cycling) (Buehler and Dill, 2016; Habib et al., 2014; Marqués et al., 2015; Schoner and Levinson, 2014; Schoner et al., 2015). In fact, designated cycling infrastructure is a crucial factor for preferring cycling for transport (de Geus et al., 2008; Heesch et al., 2015; Mertens et al., 2016a, 2016b). By protecting against motor traffic, designated cycling infrastructure is especially important for attracting new cyclists (Mertens et al., 2016b; Sallis et al., 2013). Thus, expansions of designated cycling networks may be a strategy to increase cycling for transport, which in return may contribute to improvements in public health.

Until now, however, 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, air pollution and traffic incidents. We also estimated the cost–benefit trade-off between cycling network expansions and monetized health benefits.

2. Methods

2.1. Association between cycling network and cycling mode share

2.1.1. Non-linear least square regression

Data preparations steps and coding are documented in a public GitHub repository (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 S.1). Among the 167 cities were the seven case study cities of the Physical Activity 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 mode share and population size were obtained through the European Platform on Mobility Management (EPOMM) Modal Split Tool (TEMS) (EPOMM, 2011). 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 S.2) (OpenStreetMap contributors, 2017). We also computed the street network length (km) for the PASTA cities. Analyses were conducted in R (version 3.1.1) (Table S.3) and Microsoft Excel.

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. We assumed that the explanatory properties of cycling network being associated with cycling mode share are non-linear (i.e. city-specific sensitivity to cycling network expansions in the process of becoming cycle-friendly and users starting to appreciate the increased connectivity) and limited (i.e. covariate dependence). We added bootstrap confidence intervals (CIs) based on the empirical 0.025-quantile and 0.975-quantile of the distribution resulting from 1000 bootstrap samples.

2.2. Health impact assessment

We performed a health impact assessment (HIA) for the PASTA cities to estimate how an increase in cycling might impact public health. Baseline demographic, transport and mortality data were available on city level (i.e. total population) through the PASTA project (Table 1, Tables S.4–S.14) (Dons et al., 2015; Gerike et al., 2016).

2.2.1. Scenarios

Across different scenarios (S), we assessed how the cycling mode share might change with an increase in the cycling network length by 10% (S1); 50% (S2); 100% (S3); and 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 new cycling trips were assumed to be shifted from previous car (25%) and public transport (75%) trips (Rojas-Rueda et al., 2016), to have a distance of 5 km and being traveled at a speed of 13 km/h [we considered this distance not exceeding the willingness to cycle at a speed requiring a light effort (Ainsworth et al., 2011; Rabl and de Nazelle, 2012)]. The walking share was assumed to stay constant. We estimated the impact on all-cause mortality due to changes in PA, air pollution exposure for the cyclist and the risk for fatal traffic incidents. Baseline data on all-cause mortality, PA and air pollution levels as well as traffic fatalities were collected for all seven cities (Tables S.4–S.14). 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.

2.2.2.1. Physical activity Metabolic equivalents of task (METs) were used as a measure of energy expenditure during PA. We calculated the gain in marginal METs for persons substituting car and public transport trips with cycling considering baseline PA levels (Tables S.5–S.11). A public transport trip was assumed to include a 10 min walk to public transport (Rojas-Rueda et al., 2012). We assigned the new bicycle trip 6.8 METs (Ainsworth et al., 2011; WHO. Regional Office for Europe, 2014a), and the 10 min walk to public transport 3.5 METs (Ainsworth et al., 2011).

The association between PA and mortality was quantified using a curvilinear exposure response function (ERF) (Relative Risk

Antwerp, Belgium

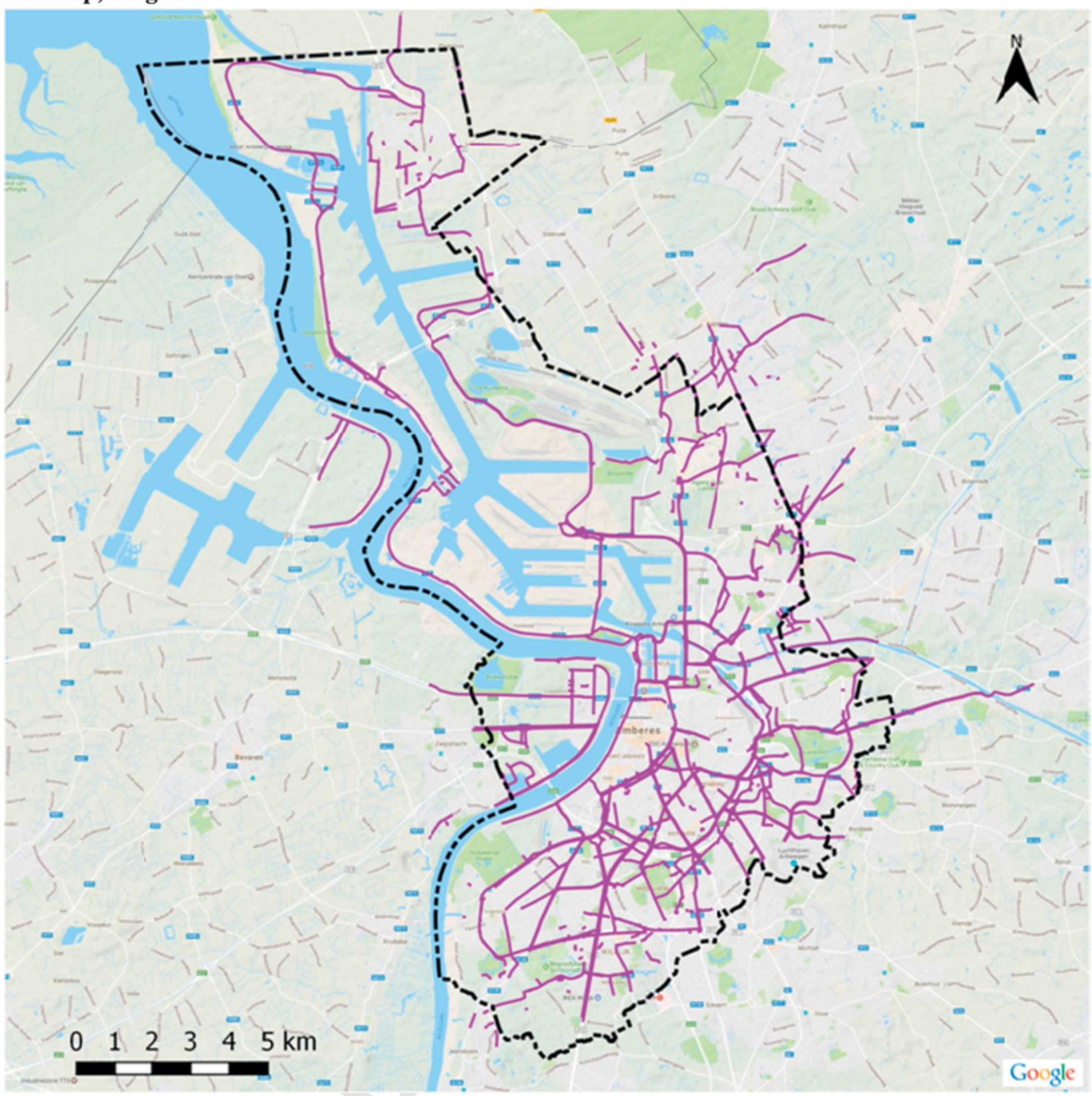

Fig. 1. Cycling networks of the seven PASTA cities.

(RR) = 0.81; 95% CI: 0.76–0.85 per 11 MET-h/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 μg/m^3 ($PM_{2.5}$) is a commonly used proxy for air pollution from motor transport (Table S.12) (Mueller et al., 2015). We considered the altered air pollution exposure for persons shifting from car or public transport (including a 10 min walk) to cycling. $PM_{2.5}$ concentration to which car drivers, public transport users, pedestrians and cyclists are exposed to were set 2.5, 1.9, 1.9 and 2.0 times higher, respectively, than background concentrations (Table S.13) (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 (μg/m^3/24-h) stratified by activity and the total dose (μg/m^3/24-h) stratified by transport mode. We calculated the equivalent $PM_{2.5}$ dose difference between cycling and motor transport (de Hartog et al., 2010). We used a linear ERF (RR = 1.07; 95% CI: 1.04–1.09 per 10 μg/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 calculated the corresponding RR and PAF. No societal co-benefits of expected air pollution reductions with a mode shift to cycling were considered.

2.2.2.3. Traffic incidents Traffic fatalities were estimated based on injury records and distance traveled. For each transport mode the risk for a fatal traffic incident per billion kilometers traveled was estimated using the reported annual average number of fatalities and kilometers traveled (Table S.14). We calculated the RR for a fatal incident for a 5 km cycling trip and compared this risk to a car and public transport trip (including a 10 min walk) of the same distance.

2.2.2.4. Sensitivity analyses As sensitivity analyses, we assumed the new cycling trips to be shifted by 75% from car and by 25% from public transport trips (Table S.15). We also applied a safety-in-numbers effect (i.e. a less than proportional increase in traffic incidents with increases in cycling) using the summary coefficient of 0.43 for cycle volume (Elvik and Bjørnskau, 2017) (Table S.16). Finally, we performed a HIA for all 167 cities, 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 (Tables S.17–S.19).

Barcelona, Spain

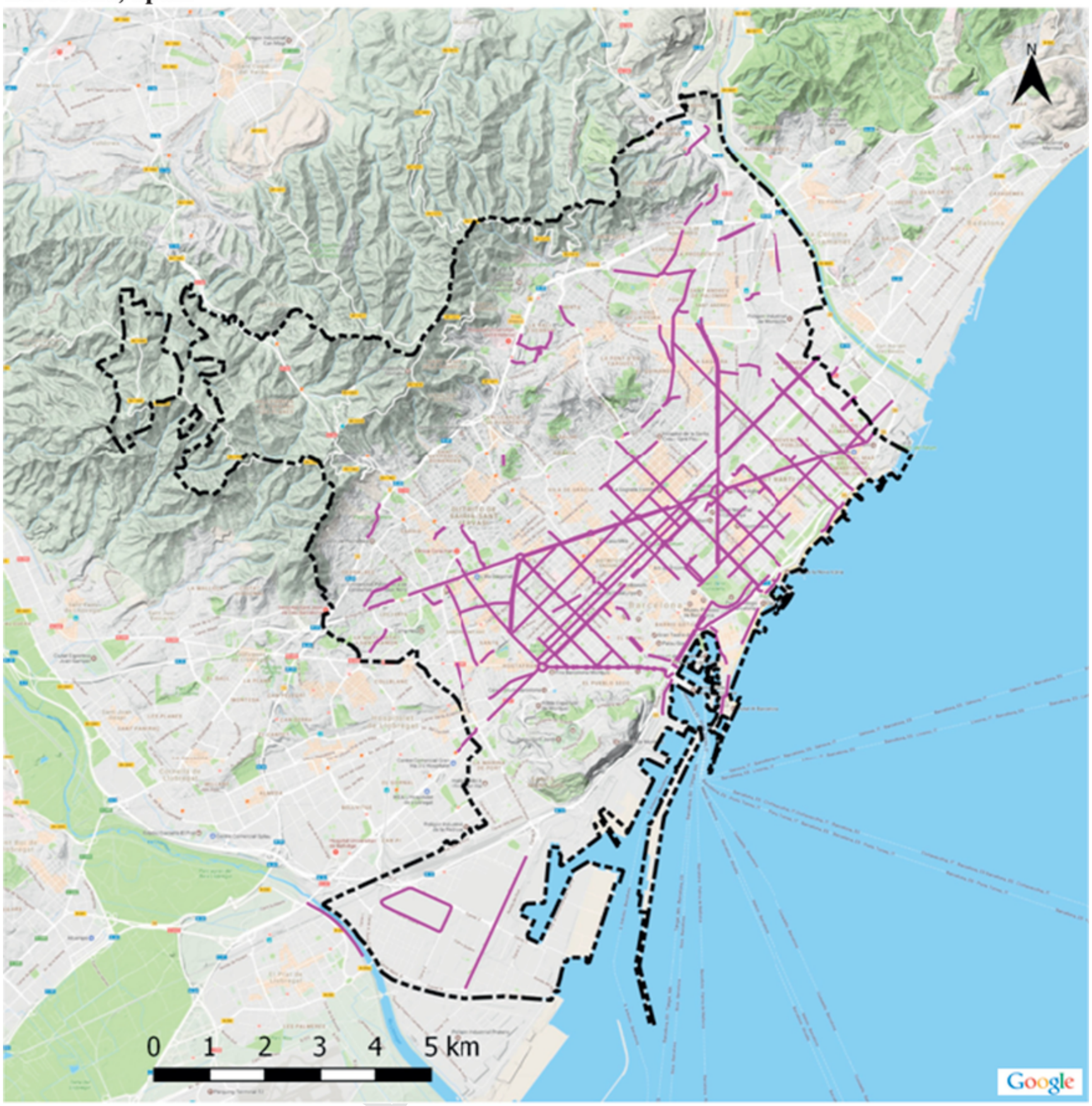

Fig. 1. (*Continued*)

2.3. Cost–benefit analysis

We estimated economic costs of cycling network expansions and compared them to estimated economic benefits of avoided premature mortality. Following the example of the Netherlands, where cycling infrastructure is commonly well-developed, we assumed that each 1 km of cycling infrastructure would cost € 2 million, which were estimated costs for reconstructing a road with mixed traffic (Schepers et al., 2015). An additional € 4000 per km/year were considered for maintenance purposes (Schepers et al., 2015). We considered a 5-year buildup of health benefits and a discounting rate of 5% (WHO. Regional Office for Europe, 2014a). We applied a time horizon of 30 years (Schepers et al., 2015), as strategic transport planning typically plans for 20–40 years ahead (Litman, 2014). We monetized health benefits by applying country-specific value of statistical life (VoSL) estimates (i.e. 3,202,968 € for Spain to 7,236,492 € for Switzerland) (Table S.20) (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 estimated 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 PASTA cities, Örebro and Antwerp showed to have the largest standardized cycling network lengths (i.e. 260 and 95 km/100,000 persons, respectively) followed by Vienna, Zurich, London, Barcelona and Rome (Table 1). Likewise, Örebro and Antwerp 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 cycling network expansions, even though growth rates were expected to vary depending on baseline cycling network length and corresponding

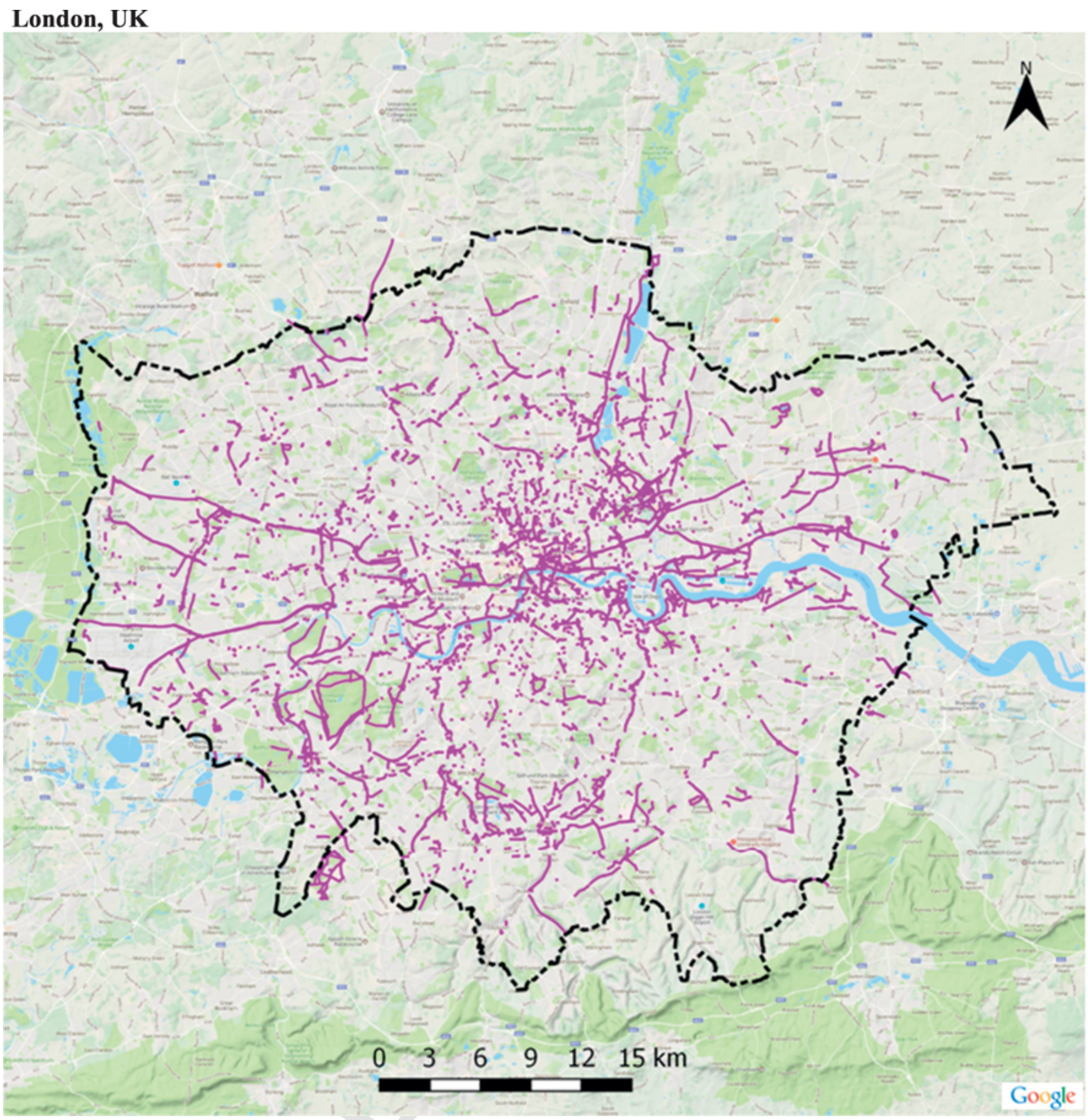

Fig. 1. (*Continued*)

mode share. Because our model caps the cycling mode share at 24.7%, no increase 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, 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 1210 premature deaths (95% CI: 447–1972) avoided each year, followed by Rome (433; 95% CI: 170–695), Barcelona (248; 95% CI: 86–410), Vienna (146; 95% CI: 40–252), Zurich (58; 95% CI: 16–100) and Antwerp (7; 95% CI: 3–11).

In standardized terms, and throughout the proportional increases in cycling network length (S1 to S3), Vienna and Zurich reaped most benefits (annually 2 to 6 premature deaths/100,000 persons avoided). In the all-streets (S4) scenario (absolute increase) and in standardized terms, Barcelona, Rome, London and Zurich reaped most benefits (annually 14 or 15 premature deaths/100,000 persons avoided). Already small increases in cycling network length (i.e. S1; 10%) provided substantial health benefits with Vienna benefiting the most in absolute terms with 31 premature deaths (95% CI: 9–54) avoided each year, followed by Rome (21; 95% CI: 8–34), London (18; 95% CI: 7–30), Barcelona (16; 95% CI: 5–26) and Zurich (9; 95% CI: 2–16).

Throughout the scenarios, estimated benefits were due to increases in PA that outweighed estimated detriments of air pollution and traffic incidents. The increase in 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 car and by 25% from public transport trips, showed even greater health benefits (Table S.15). Also the safety-in-numbers effect provided additional benefits (Table S.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 10,091 premature deaths (95% CI: 3401–16,781) avoided annually (Table S.19).

Örebro, Sweden

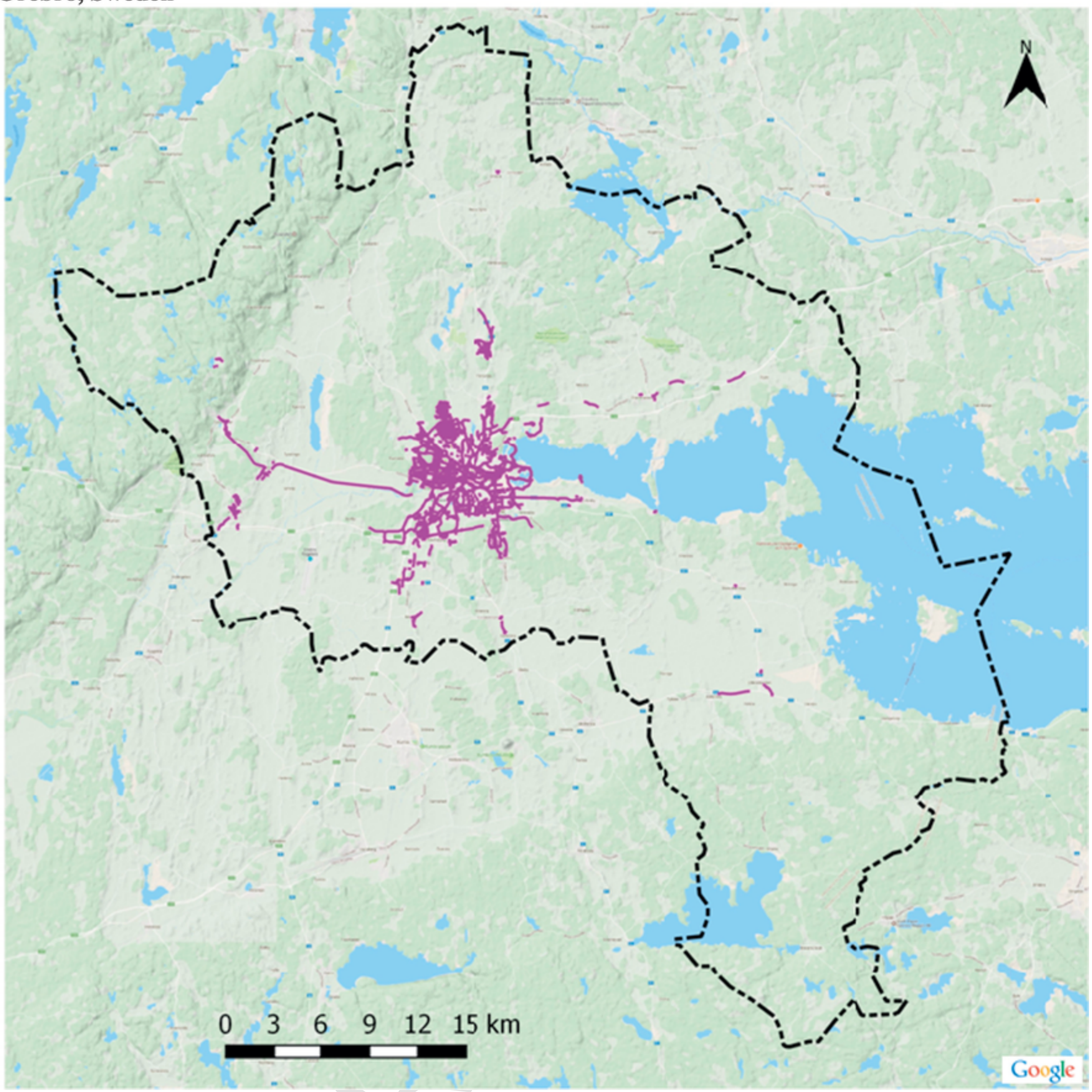

Fig. 1. (*Continued*)

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 € 70:1; Zurich € 62:1; Barcelona € 35:1 Vienna € 22:1; London € 8:1) due to the non-linearity of the cycling network-cycling mode share ERF (Table S.21).

4. Discussion

European data on cycling network length and mode share suggest that 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. 2102) could be prevented annually in six of the seven PASTA cities if the cycling network was the same as the city's street network. However, already with a 10% expansion of the cycling network, a considerable number of premature deaths (i.e. 95) was estimated to be avoidable annually in five of the seven PASTA cities, which was also the most cost-effective scenario. If all 167 European cities achieved a cycling mode share of 24.7% over 10,000 premature deaths were estimated to be avoidable annually.

To our knowledge, this is the first study evaluating the potential associations between cycling network length, 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 findings (Buehler and Dill, 2016; Buehler and Pucher, 2012; Heesch et al., 2015; Panter et al., 2016). We also estimated increases in cycling to result in net health benefits, which also agrees with previous findings (de Hartog et al., 2010; Mueller et al., 2015; Rojas-Rueda et al., 2016, 2013; Woodcock et al., 2014).

Our result of over 10,000 premature deaths avoidable in all 167 cities achieving the maximal cycling mode share of 24.7% is in line with a recent WHO study that estimated 10,000 premature deaths avoidable in over 50 major cities worldwide assuming achievement of the Copenhagen cycling mode share (i.e. 26%) for a similar population size of nearly 75 million people (WHO. Regional Office for Europe, 2014c). Thus, our study adds to the growing evidence that cycling for transport does provide substantial health benefits and should be facilitated for health promotion in the urban context.

Rome, Italy

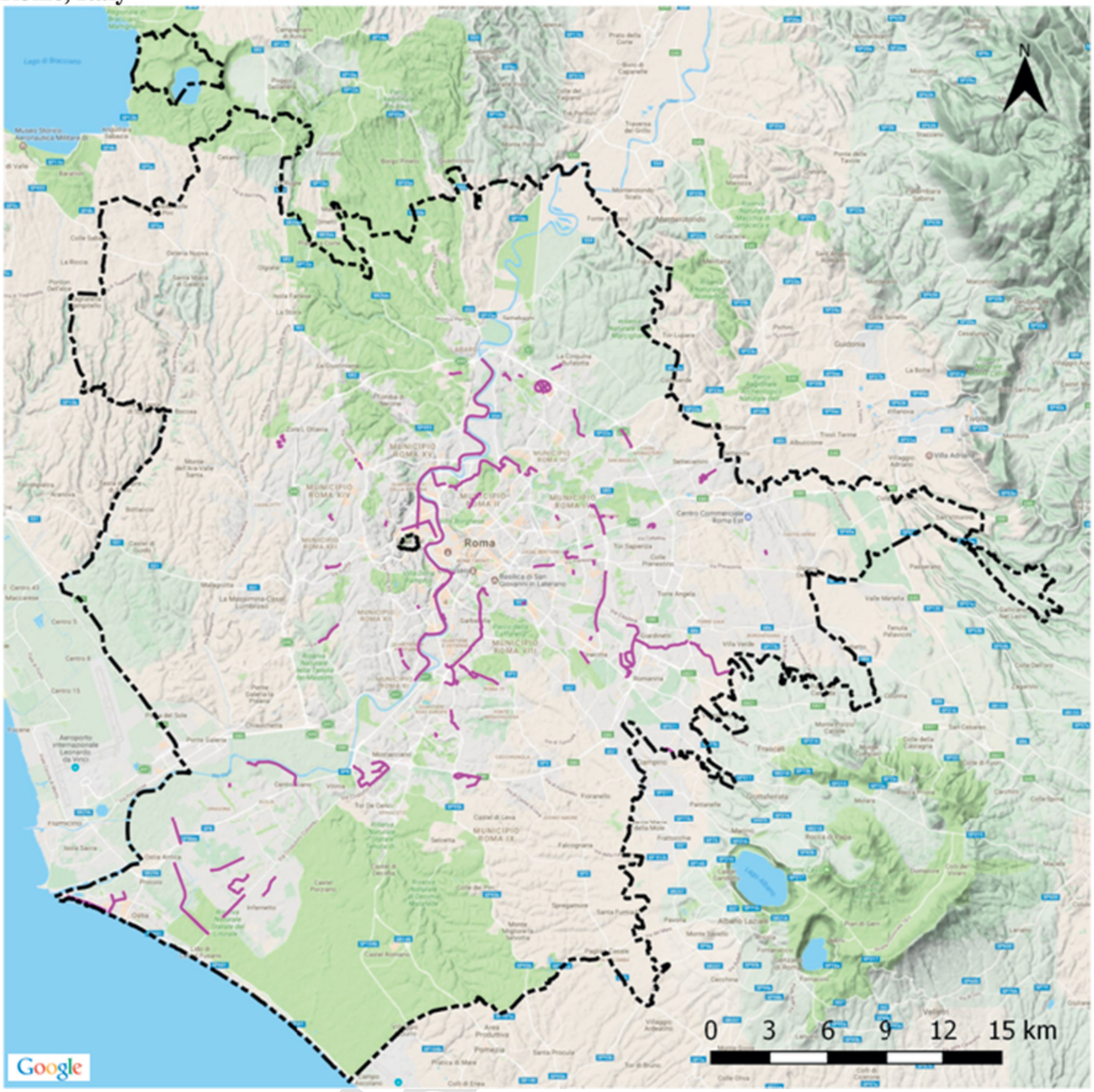

Fig. 1. (*Continued*)

The benefits of PA were estimated to outweigh detrimental effects of air pollution and traffic incidents and therefore net benefits of cycling are independent of geographical context (Mueller 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 others (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 to our modeling assumptions: (1) cycling a distance of 5 km implies a longer exposure duration than traveling the same distance by motor transport, because of varying speeds; (2) a cyclist has a higher ventilation rate due to implied physical strain. Thus, a cyclist experiences a higher uptake of pollutants for a longer duration; (3) we assumed a public transport trip to include a 10 min walk. Across all PASTA cities, walking (per km traveled) was the most hazardous mode of transport concerning traffic safety (Table S.14). Hence, the assumption that 75% of the new cycling trips substitute previous public transport trips, also shifts the risk for fatal traffic incidents. The reduced risk for a fatal traffic incident while walking to public transport makes the estimated increased risk while cycling appear less severe. Nonetheless, we did not consider health benefits resulting of reductions in air pollution background levels succeeding reductions in motor transport, thus the air pollution risk for the cyclist might have been overestimated.

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 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 1000 bootstrap samples (i.e. upper CI), then also Örebro and Antwerp could expect larger health benefits. Yet, in Örebro and Antwerp, potentially other policies should be prioritized to further promote cycling. Vienna and Zurich, on the other hand, appear to have great potential to benefit from proportional increases in cycling network length because they are at the steeper slope of the growth curve (Fig. 2). Thus, their cycling mode share appears more sensitive to expansions of the cycling network (Table 3).

London, Rome and Barcelona are expected to benefit most in absolute and standardized terms in the all-streets (S4) scenario. These three cities: (1) have larger populations; (2) benefit particularly from the large absolute increase in cycling mode share (i.e. 3%, 1% and 2% at baseline, respectively (Table 3); and (3) benefit greatly from the esti-

Vienna, Austria

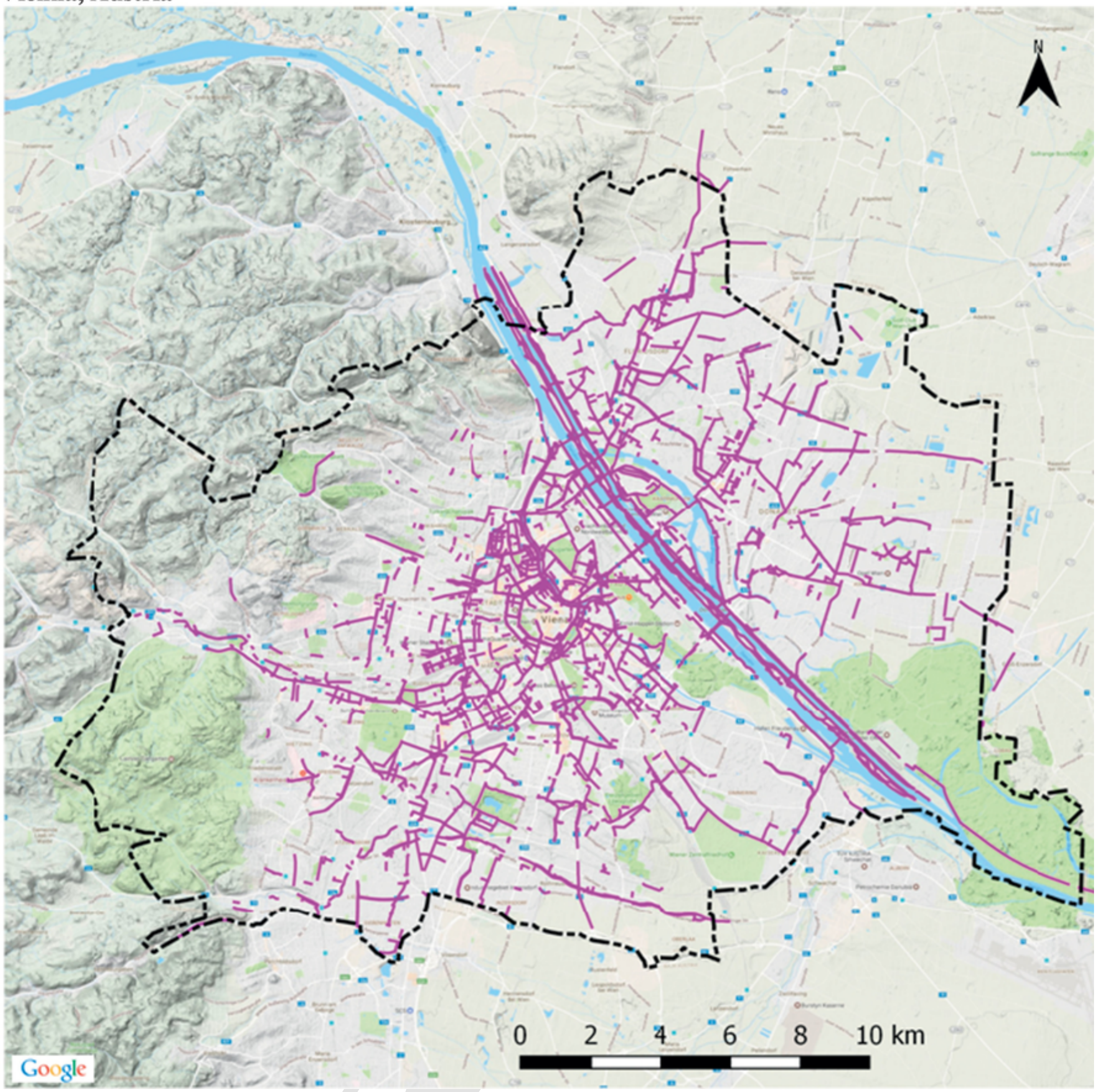

Fig. 1. (*Continued*)

mated large increases in PA [i.e. PA levels were lowest at baseline (Tables S.4–S.10)]. Generally, the cities baseline levels of PA, air pollution and traffic fatalities impact benefit estimations significantly (Rojas-Rueda et al., 2016; Tainio et al., 2016). Health benefits will be largest if at baseline the population is less physically active (and has high incidence rates for non-communicable diseases), air pollution levels are lower and traffic fatalities occur less. Despite health equity commonly being a subsidiary factor in the transport calculus, transport policies strongly determine the access to and use of the different modes of transport and thus their social significance and associated (often unequal) health pathway exposure distribution. As demonstrated in the sensitivity analysis, the greatest health benefits occur by getting people out of their own cars, because public transport provides health benefits through implied PA (i.e. 10 min walk) (Rojas-Rueda et al., 2012), and by being the safest mode of transport (Mueller et al., 2015). Hence, the parallel implementation of 'push' (e.g. making cars unattractive) and 'pull' (e.g. cycling network expansions) policies that consider equity impacts may best cater to adopt healthy transport behaviors, resulting in the largest benefits.

Policy implications of our findings may be – also under consideration of the supportive literature – that expansions of cycling networks may increase cycling, therefore, contributing to global health promotion and meeting sustainable development goals (United Nations, 2015). While other research also provides insight on 'where' cycling infrastructure should be located (e.g. the propensity to cycle tool) (Lovelace et al., 2016) and 'how it should best look like' (Mertens et al., 2016b), we simply like to express 'that' 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 low cycling mode share (i.e. Rome, Barcelona, London, Zurich and Vienna), already a 10% increase in cycling network length, which we perceive as an achievable policy for city governments, was estimated to provide considerable health and economic benefits.

4.1. Limitations and strengths

Notwithstanding, our study has limitations. First, no longitudinal data on cycling network length and mode share were available. Consequently, no conclusions on causal inferences can be drawn. Indeed, reverse causality (i.e. many cyclists leading to reinforcements of the cycling network) cannot be ruled-out. Furthermore, cities that invest in cycling infrastructure might already be congenial places for cycling.

Zurich, Switzerland

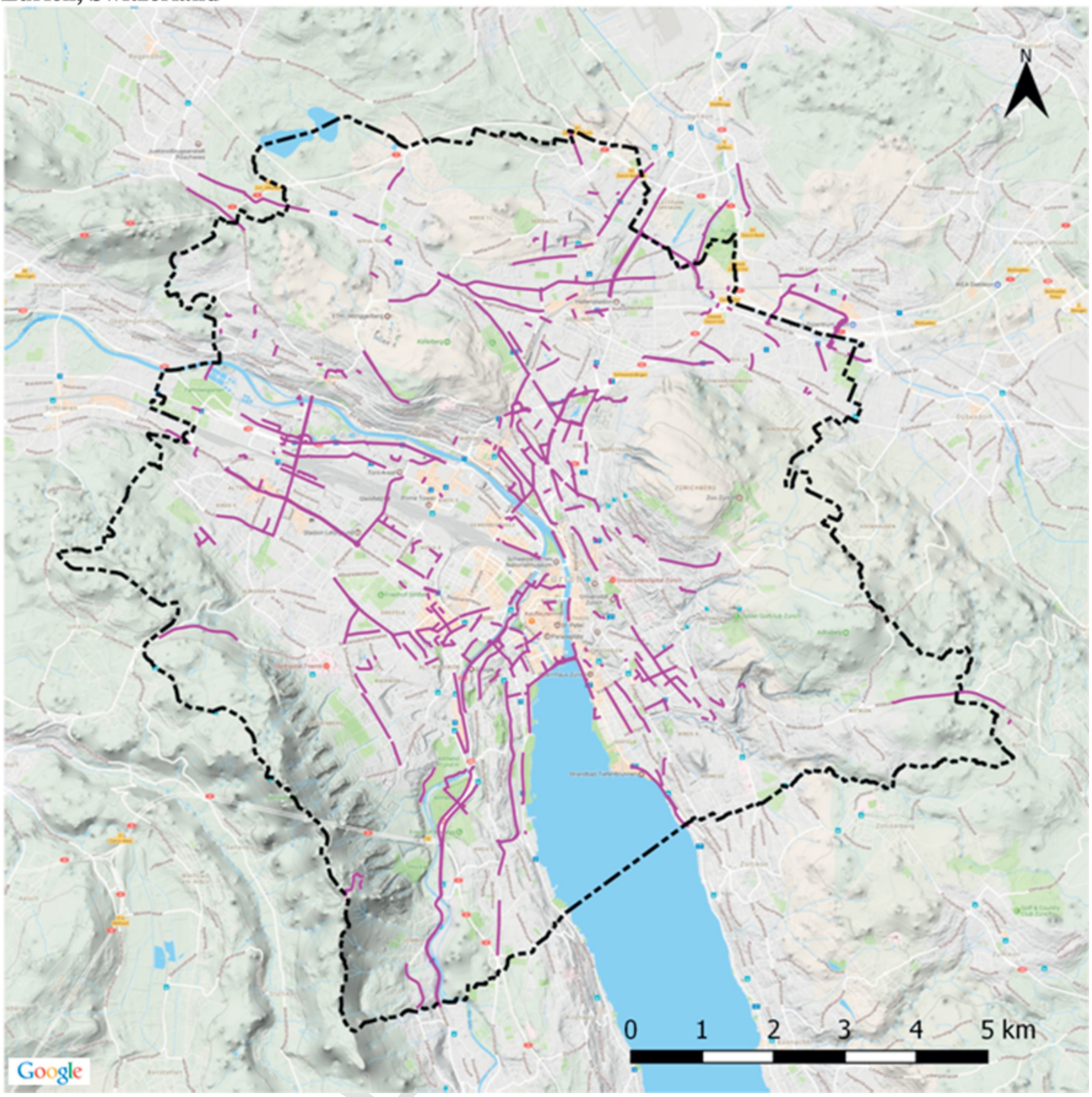

Fig. 1. (*Continued*)

Table 1
Transport infrastructure of the seven PASTA cities.

City	Country	Cycling network distance		Street network distance	
		Cycling network km (OSM)[a]	km/100,000 persons	Street network km (OSM)[a]	km/100,000 persons
Antwerp	Belgium	469.17	95.07	1651.74	334.69
Barcelona	Spain	159.54	9.84	1554.56	95.90
London	United Kingdom	969.17	11.17	16,439.74	189.54
Örebro	Sweden	361.35	260.05	3045.27	2191.60
Rome	Italy	120.64	4.20	8281.36	288.60
Vienna	Austria	715.63	39.82	3946.11	219.55
Zurich	Switzerland	118.36	28.84	1193.59	290.83

[a] OpenStreetMap (OSM) data from 10/02/2017.

Data on other built-environment, transport and socio-economic factors that were shown to influence cycling [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 available, however, are expected to alter variability in cycling mode share considerably.

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. Moreover, we considered exclusively the impacts for the actively traveling person. Societal co-benefits of reduced air and noise pollution (Buekers et al., 2015; Mueller et al., 2017b), reduced greenhouse gas emissions (Woodcock et al., 2009), and improved social cohesion and mental health (Litman, 2016a, 2016b) are expected with re-

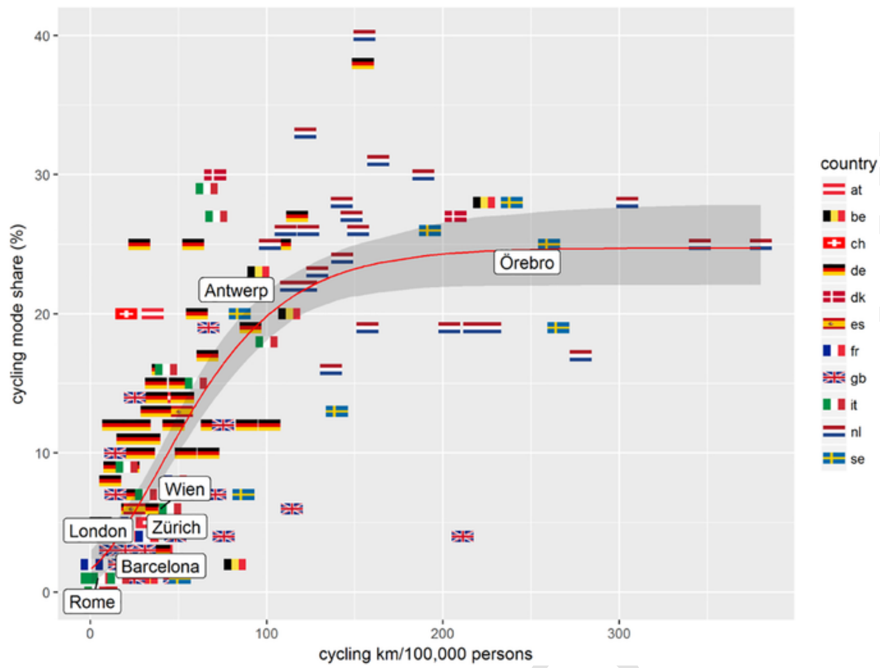

Fig. 2. Association between cycling network length and cycling mode share in European cities.

ductions in motor traffic and increases in active transport. Also, quality of life or morbidity impacts have not been considered, but are expected to be considerable (Mueller et al., 2017a). Additionally, we did not stratify our impact estimations by age, sex, or socioeconomic status even though benefit variations thereof are expected (Mueller et al., 2015). Finally, the 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 Dutch cost estimates, despite considering the reconstruction of roads, may overestimate elsewhere; also the VoSL is country-specific, which will result in differing cost–benefit ratios in other settings.

Strengths of this analysis include the novelty of being the first study to look holistically into the associations between cycling network, cycling mode share and associated health impacts across 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 (Salmon and Mueller, 2017) add strength and ensure reproducibility.

5. Conclusions

Expansions of cycling networks were associated with increases in cycling in European cities. Increases in cycling were estimated to provide considerable health and economic benefits.

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Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ypmed.2017.12.011.

Table 2
Baseline transport data for the seven PASTA cities.

Demographic and transport data				Mode share data										
				Car				Public transport				Bicycle		
City	Population	Trips/day	Trips/person/day	%	Persons/day	Mean distance (km)	Mean time(h)	%	Persons/day	Mean distance (km)	Mean time (h)	%	Persons/day	Mean distance (km)
Antwerp[a]	493,517	1,362,107	2.8	41	202,342	11.81	0.30	16	78,963	9.81	0.57	23	113,509	3.84
Barcelona[b]	1,620,943	4,908,402	3.7	26	344,915	8.77	0.43	40	530,638	6.71	0.55	2	26,532	3.50
London[c]	8,673,713	19,740,640	2.5	38	2,980,311	7.00	0.38	29	2,274,448	7.00	0.75	3	235,288	3.00
Örebro[d]	138,952	276,000	2.6	55	58,385	7.90	0.30	9	9554	10.00	0.62	25	26,538	3.30
Rome[e]	2,869,461	4,900,000	2.6	54	1,017,692	13.00	0.73	29	546,538	11.50	0.82	1	18,846	7.70
Vienna[f]	1,797,337	4,251,000	3.4	27	340,585	12.00	0.40	39	491,955	8.20	0.47	6	75,685	3.30
Zurich[g]	410,404	1,559,535	3.8	30	123,121	5.27	0.31	39	160,058	7.84	0.52	4	16,416	2.77

[a] Demographic data is from 2011, mode share data is from 2011, and mean distance and time traveled is from 2013.
[b] Demographic data is from 2012, mode share data is from 2012, and mean distance and time traveled is from 2006, 2015.
[c] Demographic data is from 2015, mode share data is for 2012, and mean distance and time traveled is for 2013.
[d] Demographic data is from 2012, mode share data is for 2011, and mean distance and time traveled is for 2011.
[e] Demographic data is from 2014, mode share data is for 2014, and mean distance and time traveled is for 2014.
[f] Demographic data is from 2015, mode share data is for 2012, and mean distance and time traveled is for 2013.
[g] Demographic data is from 2015, mode share data is for 2010, and mean distance and time traveled is for 2010.

Table 3
Scenarios and mode share estimations.

City	Mode share				Cycling network	
	Car (%)	Public transport (%)	Cycling (%)	Walking (%)	Cycling km	Cycling km/100,000 persons
Antwerp (baseline)	41.00	16.00	23.00	20.00	469.17	95.07
S1 10%	41.67	18.02	20.31	20.00	516.09	104.57
S2 50%	41.02	16.05	22.93	20.00	703.76	142.60
S3 100%	40.71	15.12	24.18	20.00	938.34	190.13
S4 all-streets	40.57	14.70	24.74	20.00	1651.74	334.69
Barcelona (baseline)	26.00	40.00	2.00	32.00	159.54	9.84
S1 10%	25.73	39.18	3.09	32.00	175.49	10.83
S2 50%	25.56	38.68	3.76	32.00	239.31	14.76
S3 100%	25.33	37.99	4.68	32.00	319.08	19.68
S4 all-streets	21.68	27.03	19.30	32.00	1554.56	95.90
London (baseline)	38.00	29.00	3.00	30.00	969.17	11.17
S1 10%	37.92	28.76	3.32	30.00	1066.09	12.29
S2 50%	37.72	28.16	4.12	30.00	1453.76	16.76
S3 100%	37.45	27.34	5.21	30.00	1938.34	22.35
S4 all-streets	32.70	13.09	24.21	30.00	1,6439.74	189.54
Örebro (baseline)	55.00	9.00	25.00	11.00	361.35	260.05
S1 10%	55.08	9.23	24.69	11.00	397.49	286.06
S2 50%	55.07	9.20	24.74	11.00	542.03	390.08
S3 100%	55.07	9.20	24.74	11.00	722.70	520.11
S4 all-streets	55.07	9.20	24.74	11.00	3045.27	2191.60
Rome (baseline)	54.00	29.00	1.00	16.00	120.64	4.20
S1 10%	53.71	28.12	2.17	16.00	132.70	4.62
S2 50%	53.65	27.95	2.40	16.00	180.96	6.31
S3 100%	53.57	27.72	2.71	16.00	241.28	8.41
S4 all-streets	48.07	11.22	24.71	16.00	8281.36	288.60
Vienna (baseline)	27.00	39.00	6.00	28.00	715.63	39.82
S1 10%	26.01	36.02	9.97	28.00	787.19	43.80
S2 50%	25.14	33.41	13.46	28.00	1073.45	59.72
S3 100%	24.23	30.68	17.10	28.00	1431.26	79.63
S4 all-streets	22.38	25.13	24.49	28.00	3946.11	219.55
Zurich (baseline)	30.00	39.00	4.00	27.00	118.36	28.84
S1 10%	29.19	36.58	7.23	27.00	130.20	31.72
S2 50%	28.54	34.61	9.85	27.00	177.54	43.26
S3 100%	27.75	32.24	13.01	27.00	236.72	57.68
S4 all-streets	24.82	23.47	24.71	27.00	1193.59	290.83

S = Scenario.

Table 4
Mortality impact (avoided premature deaths/year) for each scenario.

City	Physical activity (deaths avoided) (95% CI)	Air pollution active traveler (additional deaths) (95% CI)	Traffic incidents (additional deaths) (95% CI)	Total deaths avoided (95% CI)	Total deaths (per 100,000 persons) avoided (95% CI)
Antwerp					
S1 10%	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)
S2 50%	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)
S3 100%	−6 (−9;−5)	1 (1;2)	0 (−2;2)	−5 (−8;−2)	−1 (−2;0)
S4 all-streets	−9 (−13;−7)	2 (1;2)	0 (−3;3)	−7 (−11;−3)	−1 (−2;0)
Barcelona					
S1 10%	−21 (−30;−16)	4 (1;5)	2 (−5;9)	−16 (−26;-5)	−1 (−2;0)
S2 50%	−35 (−48;−25)	6 (1;8)	3 (−8;15)	−25 (−42;−9)	−2 (−4;1)
S3 100%	−53 (−73;−39)	9 (2;12)	5 (−13;22)	−38 (−64;−13)	−2 (−6;1)
S4 all-streets	−340 (−474;−249)	60 (12;77)	31 (−81;144)	−248 (−410;−86)	−15 (−36;5)
London					
S1 10%	−24 (−34;−18)	4 (2;5)	2 (−6;10)	−18 (−30;−7)	0 (−1;0)
S2 50%	−85 (−119;−63)	14 (8;18)	8 (−21;36)	−64 (−104;-24)	−1 (−3;1)
S3 100%	−169 (−235;−123)	28 (16;35)	15 (−41;70)	−126 (−206;−47)	−1 (−6;3)
S4 all-streets	−1617 (−2255;−1185)	265 (155;337)	142 (−393;677)	−1210 (−1972;−447)	−14 (−56;28)
Örebro					
S1 10%	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)
S2 50%	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)
S3 100%	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)
S4 all-streets	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)	0 (0;0)
Rome					
S1 10%	−27 (−38;−20)	5 (3;6)	2 (−8;11)	−21 (−34;−8)	−1 (−2;0)
S2 50%	−33 (−46;−24)	6 (3;7)	2 (−9;13)	−26 (−41;−10)	−1 (−2;1)
S3 100%	−40 (−56;−29)	7 (4;9)	2 (−11;15)	−31 (−50;−12)	−1 (−3;1)
S4 all-streets	−557 (−776; −408)	94 (55;119)	31 (−153;215)	−433 (−695; −170)	−15 (−40;10)
Vienna					
S1 10%	−47 (−66;−34)	13 (8;17)	2 (−14;18)	−31 (−54;-9)	−2 (−4;1)
S2 50%	−88 (−124;−64)	25 (15;32)	4 (−25;34)	−59 (−102;−16)	−3 (−8;2)
S3 100%	−131 (−184;−96)	38 (22;48)	6 (−38;50)	−88 (−151;−24)	−5 (−13;3)
S4 all-streets	−219 (−307;−160)	63 (36;79)	10 (−63;84)	−146 (−252;−40)	−8 (−21;5)
Zurich					
S1 10%	−14 (−19;−10)	3 (2;3)	2 (−3;7)	−9 (−16;−2)	−2 (−4;−1)
S2 50%	−25 (−35;−18)	5 (3;6)	3 (−5;12)	−16 (−28;−4)	−4 (−7;−1)
S3 100%	−38 (−53;-28)	7 (4;9)	5 (−7;18)	−25 (−43;−7)	−6 (−11;−2)
S4 all-streets	−87 (−122;−63)	17 (10;21)	12 (−17;42)	−58 (−100;−16)	−14 (−25;−3)

S = Scenario; 95% CI = 95% confidence interval.

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