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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 1,210 premature deaths (95% CI: 447-1,972) 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.

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## **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 <sub>2.5</sub> | particulate matter with a diameter of $\leq 2.5 \mu\text{g}/\text{m}^3$ |
| RR                | relative risk   |
| S                 | scenario  |
| SD                | standard deviation  |
| TEMS              | European Platform on Mobility Management Modal Split Tool               |
| VoSL              | value of statistical life   |

1 **ABSTRACT**

2 We conducted a health impact assessment (HIA) of cycling network expansions in  
3 seven European cities. We modeled the association between cycling network length and  
4 cycling mode share and estimated health impacts of the expansion of cycling networks.  
5 First, we performed a non-linear least square regression to assess the relationship  
6 between cycling network length and cycling mode share for 167 European cities.  
7 Second, we conducted a quantitative HIA for the seven cities of different scenarios (S)  
8 assessing how an expansion of the cycling network [i.e. 10% (S1); 50% (S2); 100%  
9 (S3), and all-streets (S4)] would lead to an increase in cycling mode share and estimated  
10 mortality impacts thereof. We quantified mortality impacts for changes in physical  
11 activity, air pollution and traffic incidents. Third, we conducted a cost-benefit analysis.  
12 The cycling network length was associated with a cycling mode share of up to 24.7% in  
13 European cities. The all-streets scenario (S4) produced greatest benefits through  
14 increases in cycling for London with 1,210 premature deaths (95% CI: 447-1,972)  
15 avoidable annually, followed by Rome (433; 95% CI: 170-695), Barcelona (248; 95%  
16 CI: 86-410), Vienna (146; 95% CI: 40-252), Zurich (58; 95% CI: 16-100) and Antwerp  
17 (7; 95% CI: 3-11). The largest cost-benefit ratios were found for the 10% increase in  
18 cycling networks (S1). If all 167 European cities achieved a cycling mode share of  
19 24.7% over 10,000 premature deaths could be avoided annually. In European cities,  
20 expansions of cycling networks were associated with increases in cycling and estimated  
21 to provide health and economic benefits.

22

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

## 25 1. INTRODUCTION

26 There is increasing awareness of the adverse effects of the car-centric urban mobility  
27 plans of previous decades (Nieuwenhuijsen and Khreis, 2016). Concerns relate to  
28 contemporary sedentarism, ecological issues of air and noise pollution, greenhouse gas  
29 emissions and the loss of natural outdoor environments, but also to economic issues of  
30 space scarcity, congestion costs and financing infrastructure (Khreis et al., 2016;  
31 Marqués et al., 2015).

32

33 Promoting a mode shift to cycling for transport has been proposed as a promising  
34 strategy in urban environments to overcome these issues (Mueller et al., 2015). Cycling  
35 can increase total physical activity (PA) levels (Foley et al., 2015; Goodman et al.,  
36 2014; Sahlqvist et al., 2013), and is a non-emitting mode of transport. However, to  
37 facilitate a shift to cycling, well-designed and safe infrastructure is needed (Mertens et  
38 al., 2016a; Pucher et al., 2010).

39

40 Recent research evidence indicates positive associations between cycling network  
41 length and cycling mode share (i.e. percentage of all trips done cycling) (Buehler and  
42 Dill, 2016; Habib et al., 2014; Marqués et al., 2015; Schoner and Levinson, 2014;  
43 Schoner et al., 2015). In fact, designated cycling infrastructure is a crucial factor for  
44 preferring cycling for transport (de Geus et al., 2008; Heesch et al., 2015; Mertens et al.,  
45 2016a, 2016b). By protecting against motor traffic, designated cycling infrastructure is  
46 especially important for attracting new cyclists (Mertens et al., 2016b; Sallis et al.,  
47 2013). Thus, expansions of designated cycling networks may be a strategy to increase  
48 cycling for transport, which in return may contribute to improvements in public health.

49 Until now, however, the exposure response relationship between cycling network and  
50 cycling mode share in European cities is unknown. Therefore, we assessed (1) the  
51 association between cycling network length (km) and cycling mode share (%) and (2)  
52 how an increase in cycling mode share might alter expected mortality in terms of  
53 changes in PA, air pollution and traffic incidents. We also estimated the cost-benefit  
54 trade-off between cycling network expansions and monetized health benefits.

55

## 56 **2. METHODS**

### 57 **2.1 Association between cycling network and cycling mode share**

#### 58 *2.1.1 Non-linear least square regression*

59 Data preparations steps and coding are documented in a public GitHub repository  
60 (Salmon and Mueller, 2017). We obtained data on population size, cycling mode share  
61 and cycling network length for 167 cities located in 11 European countries (4 Austria, 7  
62 Belgium, 2 Denmark, 20 France, 47 Germany, 15 Italy, 23 Netherlands, 14 Spain, 9  
63 Sweden, 2 Switzerland, 24 United Kingdom) (**Table S.1**). Amongst the 167 cities were  
64 the seven case study cities of the Physical Activity through Sustainable Transport  
65 Approaches (PASTA) project (i.e. Antwerp, Barcelona, London, Rome, Örebro,  
66 Vienna, Zurich) (**Fig. 1**) (Gerike et al., 2016). The other 160 cities were chosen based  
67 on (1) their geographic representativeness of Northern, Central and Southern Europe,  
68 (2) population size  $\geq 100,000$  persons, (3) the availability of mode share data not being  
69 older than 2006 and (4) the availability of spatial boundaries.

70

71 Data on mode share and population size were obtained through the European Platform  
72 on Mobility Management (EPOMM) Modal Split Tool (TEMS) (EPOMM, 2011).  
73 Spatial administrative municipality boundaries were obtained from the Database of



74 Global Administrative Areas (GADM) (Hijmans, 2009), the UK data service (Office for  
75 National Statistics, 2011), and the Swedish lantmäteriet (Swedish Ministry of Enterprise  
76 and Innovation., 2016). We used OpenStreetMap (OSM) to compute cycling network  
77 lengths for all 167 cities (**Table 1**) using labels of designated, non-shared cycling ways  
78 (**Table S.2**) (OpenStreetMap contributors, 2017). We also computed the street network  
79 length (km) for the PASTA cities. Analyses were conducted in R (version 3.1.1) (**Table**  
80 **S.3**) and Microsoft Excel.

81

82 We standardized the computed cycling network length of the 167 cities by population  
83 size. We used ‘cycling network km/ 100,000 persons’ as the explanatory variable and  
84 performed a non-linear least square regression (i.e. Gompertz growth model) to  
85 calculate the corresponding cycling mode share (%) with  $y(t) = ae^{-be^{-ct}}$ , where  $a$  is  
86 the asymptote (i.e. maximal cycling mode share associated with cycling network),  $b$  sets  
87 the displacement along the  $x$ -axis and  $c$  sets the displacement along the  $y$ -axis (i.e.  
88 growth rate),  $t$  is the cycling network km/ 100,000 persons. We assumed that the  
89 explanatory properties of cycling network being associated with cycling mode share are  
90 non-linear (i.e. city-specific sensitivity to cycling network expansions in the process of  
91 becoming cycle-friendly and users starting to appreciate the increased connectivity) and  
92 limited (i.e. covariate dependence). We added bootstrap confidence intervals (CIs)  
93 based on the empirical 0.025-quantile and 0.975-quantile of the distribution resulting  
94 from 1,000 bootstrap samples.

95

96

## 97 **2.2 Health impact assessment**

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

102

### 103 *2.2.1 Scenarios*

104 Across different scenarios (S), we assessed how the cycling mode share might change  
105 with an increase in the cycling network length by 10% (S1); 50% (S2); 100% (S3); and  
106 if all streets (km/ 100,000 persons) of the city provided designated cycling infrastructure  
107 (S4 – all-streets).

108

### 109 *2.2.2 Health impact assessment model*

110 The new cycling trips were assumed to be shifted from previous car (25%) and public  
111 transport (75%) trips (Rojas-Rueda et al., 2016), to have a distance of 5 km and being  
112 traveled at a speed of 13 km/h [we considered this distance not exceeding the  
113 willingness to cycle at a speed requiring a light effort (Ainsworth et al., 2011; Rabl and  
114 de Nazelle, 2012)]. The walking share was assumed to stay constant. We estimated the  
115 impact on all-cause mortality due to changes in PA, air pollution exposure for the  
116 cyclist and the risk for fatal traffic incidents. Baseline data on all-cause mortality, PA  
117 and air pollution levels as well as traffic fatalities were collected for all seven cities  
118 (**Tables S.4-S.14**). 95% CIs for the overall impact were based on the pooled standard  
119 deviation (SD) of PA, air pollution and fatal traffic incidents. We assumed the mortality  
120 risk to be normally distributed.

121

122

123 *2.2.2.1 Physical activity*

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

131

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

138

139 *2.2.2.2 Air pollution exposure cyclist*

140 Particulate matter (PM) with a diameter of  $\leq 2.5 \mu\text{g}/\text{m}^3$  (PM<sub>2.5</sub>) is a commonly used  
141 proxy for air pollution from motor transport (**Table S.12**) (Mueller et al., 2015). We  
142 considered the altered air pollution exposure for persons shifting from car or public  
143 transport (including a 10 minute walk) to cycling. PM<sub>2.5</sub> concentration to which car  
144 drivers, public transport users, pedestrians and cyclists are exposed to were set 2.5, 1.9,  
145 1.9 and 2.0 times higher, respectively, than background concentrations (**Table S.13**) (de  
146 Nazelle et al., 2017). Ventilation rates for different leisure and transport activities were  
147 available from previous assessments (Rojas-Rueda et al., 2016, 2012). We calculated

148 the daily inhaled PM<sub>2.5</sub> dose ( $\mu\text{g}/\text{m}^3/24\text{-h}$ ) stratified by activity and the total dose  
149 ( $\mu\text{g}/\text{m}^3/24\text{-h}$ ) stratified by transport mode. We calculated the equivalent PM<sub>2.5</sub> dose  
150 difference between cycling and motor transport (de Hartog et al., 2010). We used a  
151 linear ERF (RR=1.07; 95% CI: 1.04-1.09 per 10  $\mu\text{g}/\text{m}^3$  PM<sub>2.5</sub> annual mean) to quantify  
152 the association between PM<sub>2.5</sub> exposure and mortality (WHO. Regional Office for  
153 Europe, 2014b). We calculated the corresponding RR and PAF. No societal co-benefits  
154 of expected air pollution reductions with a mode shift to cycling were considered.

155

#### 156 *2.2.2.3 Traffic incidents*

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

163

#### 164 *2.2.2.4 Sensitivity analyses*

165 As sensitivity analyses, we assumed the new cycling trips to be shifted by 75% from car  
166 and by 25% from public transport trips (**Table S.15**). We also applied a safety-in-  
167 numbers effect (i.e. a less than proportional increase in traffic incidents with increases  
168 in cycling) using the summary coefficient of 0.43 for cycle volume (Elvik and  
169 Bjørnskau, 2017) (**Table S.16**). Finally, we performed a HIA for all 167 cities,  
170 supposing achievement of the maximal cycling mode share predicted by our model (i.e.  
171 24.7%). For model inputs, we used the mean of the PASTA city data for transport,  
172 exposures and mortality (**Tables S.17-S.19**).

## 173 **2.3 Cost-benefit analysis**

174 We estimated economic costs of cycling network expansions and compared them to  
175 estimated economic benefits of avoided premature mortality. Following the example of  
176 the Netherlands, where cycling infrastructure is commonly well-developed, we assumed  
177 that each 1 km of cycling infrastructure would cost € 2 million, which were estimated  
178 costs for reconstructing a road with mixed traffic (Schepers et al., 2015). An additional  
179 € 4,000 per km/ year were considered for maintenance purposes (Schepers et al., 2015).  
180 We considered a 5-year buildup of health benefits and a discounting rate of 5% (WHO.  
181 Regional Office for Europe, 2014a). We applied a time horizon of 30 years (Schepers et  
182 al., 2015), as strategic transport planning typically plans for 20-40 years ahead (Litman,  
183 2014). We monetized health benefits by applying country-specific value of statistical  
184 life (VoSL) estimates (i.e. 3,202,968 € for Spain to 7,236,492 € for Switzerland) (**Table**  
185 **S.20**) (WHO. Regional Office for Europe, 2014a). No de-congestion or other benefits  
186 were monetized.

187

## 188 **3. RESULTS**

### 189 **3.1 Association between cycling network distance and cycling mode share**

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

194

195 Regarding the PASTA cities, Örebro and Antwerp showed to have the largest  
196 standardized cycling network lengths (i.e. 260 and 95 km/ 100,000 persons,  
197 respectively) followed by Vienna, Zurich, London, Barcelona and Rome (**Table 1**).

198 Likewise, Örebro and Antwerp had the largest cycling mode share at baseline (25% and  
199 23%, respectively) followed by Vienna, Zurich, London, Barcelona and Rome (**Table**  
200 **2**). According to our model, the PASTA cities, except Örebro and Antwerp, had great  
201 potential to increase their cycling mode share through cycling network expansions, even  
202 though growth rates were expected to vary depending on baseline cycling network  
203 length and corresponding mode share. Because our model caps the cycling mode share  
204 at 24.7%, no increase in cycling was expected for Örebro as at baseline already 25% of  
205 all trips were carried out cycling. Also in Antwerp where already 23% of all trips were  
206 done cycling, the cycling network length would need to be doubled to achieve a 1%  
207 increase in cycling mode share (**Table 3**).

208

### 209 **3.2 Estimated health impacts**

210 The PASTA cities were estimated to benefit from an increase in cycling, except for  
211 Örebro, and Antwerp benefiting only to a small extent (**Table 4**). The all-streets  
212 scenario (S4) produced the greatest health benefits through increases in cycling for  
213 London with 1,210 premature deaths (95% CI: 447-1,972) avoided each year, followed  
214 by Rome (433; 95% CI: 170-695), Barcelona (248; 95% CI: 86-410), Vienna (146; 95%  
215 CI: 40-252), Zurich (58; 95% CI: 16-100) and Antwerp (7; 95% CI: 3-11).

216

217 In standardized terms, and throughout the proportional increases in cycling network  
218 length (S1 to S3), Vienna and Zurich reaped most benefits (annually 2 to 6 premature  
219 deaths/ 100,000 persons avoided). In the all-streets (S4) scenario (absolute increase) and  
220 in standardized terms, Barcelona, Rome, London and Zurich reaped most benefits  
221 (annually 14 or 15 premature deaths/ 100,000 persons avoided). Already small increases  
222 in cycling network length (i.e. S1; 10%) provided substantial health benefits with

223 Vienna benefiting the most in absolute terms with 31 premature deaths (95% CI: 9-54)  
224 avoided each year, followed by Rome (21; 95% CI: 8-34), London (18; 95% CI: 7-30),  
225 Barcelona (16; 95% CI: 5-26) and Zurich (9; 95% CI: 2-16).

226

227 Throughout the scenarios, estimated benefits were due to increases in PA that  
228 outweighed estimated detriments of air pollution and traffic incidents. The increase in  
229 cycling provided greater risks in terms of air pollution exposure than the expected  
230 increase in fatal traffic incidents.

231

232 The sensitivity analysis assuming the new cycling trips being shifted by 75% from car  
233 and by 25% from public transport trips, showed even greater health benefits (**Table**  
234 **S.15**). Also the safety-in-numbers effect provided additional benefits (**Table S.16**). The  
235 HIA for all 167 European cities, with a total population of 75.2 million people,  
236 achieving a cycling mode share of 24.7% resulted in 10,091 premature deaths (95% CI:  
237 3,401-16,781) avoided annually (**Table S.19**).

238

### 239 **3.3 Estimated cost-benefit impacts**

240 The cost-benefit analysis showed generally positive cost-benefit trade-offs, except for  
241 Örebro and Antwerp where no or only small health benefits were expected. The largest  
242 cost-benefit ratios were found for the 10% increase in cycling network (S1) (Rome €  
243 70:1; Zurich € 62:1; Barcelona € 35:1 Vienna € 22:1; London € 8:1) due to the non-  
244 linearity of the cycling network-cycling mode share ERF (**Table S.21**).

245

#### 246 4. DISCUSSION

247 European data on cycling network length and mode share suggest that a designated  
248 cycling network is associated with a cycling mode share of up to 24.7%. We estimated  
249 that a large number of premature deaths (i.e. 2,102) could be prevented annually in six  
250 of the seven PASTA cities if the cycling network was the same as the city's street  
251 network. However, already with a 10% expansion of the cycling network, a  
252 considerable number of premature deaths (i.e. 95) was estimated to be avoidable  
253 annually in five of the seven PASTA cities, which was also the most cost-effective  
254 scenario. If all 167 European cities achieved a cycling mode share of 24.7% over 10,000  
255 premature deaths were estimated to be avoidable annually.

256

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

265

266 Our result of over 10,000 premature deaths avoidable in all 167 cities achieving the  
267 maximal cycling mode share of 24.7% is in line with a recent WHO study that  
268 estimated 10,000 premature deaths avoidable in over 50 major cities worldwide  
269 assuming achievement of the Copenhagen cycling mode share (i.e. 26%) for a similar  
270 population size of nearly 75 million people (WHO. Regional Office for Europe, 2014c).



271 Thus, our study adds to the growing evidence that cycling for transport does provide  
272 substantial health benefits and should be facilitated for health promotion in the urban  
273 context.

274

275 The benefits of PA were estimated to outweigh detrimental effects of air pollution and  
276 traffic incidents and therefore net benefits of cycling are independent of geographical  
277 context (Mueller et al., 2015). In contrast to some studies (Buekers et al., 2015; Dhondt  
278 et al., 2013; Rabl and de Nazelle, 2012; Woodcock et al., 2014), but in agreement with  
279 others (Rojas-Rueda et al., 2012, 2011), we found air pollution exposure for the cyclist  
280 to be a greater mortality risk than having a fatal traffic incident. This is due to our  
281 modeling assumptions: (1) cycling a distance of 5 km implies a longer exposure  
282 duration than traveling the same distance by motor transport, because of varying speeds;  
283 (2) a cyclist has a higher ventilation rate due to implied physical strain. Thus, a cyclist  
284 experiences a higher uptake of pollutants for a longer duration; (3) we assumed a public  
285 transport trip to include a 10 minute walk. Across all PASTA cities, walking (per km  
286 traveled) was the most hazardous mode of transport concerning traffic safety (**Table**  
287 **S.14**). Hence, the assumption that 75% of the new cycling trips substitute previous  
288 public transport trips, also shifts the risk for fatal traffic incidents. The reduced risk for a  
289 fatal traffic incident while walking to public transport makes the estimated increased  
290 risk while cycling appear less severe. Nonetheless, we did not consider health benefits  
291 resulting of reductions in air pollution background levels succeeding reductions in  
292 motor transport, thus the air pollution risk for the cyclist might have been  
293 overestimated.

294

295 As the length of the cycling network was associated with a cycling mode share of up to  
296 24.7%, for Örebro and Antwerp no or only small increases in cycling due to increases in  
297 cycling network are expected, which in return results in no or only small health benefits.  
298 However, if the true association between cycling network length and cycling mode  
299 share was better represented by the 0.975-quantile of the distribution of the 1,000  
300 bootstrap samples (i.e. upper CI), then also Örebro and Antwerp could expect larger  
301 health benefits. Yet, in Örebro and Antwerp, potentially other policies should be  
302 prioritized to further promote cycling. Vienna and Zurich, on the other hand, appear to  
303 have great potential to benefit from proportional increases in cycling network length  
304 because they are at the steeper slope of the growth curve (**Fig. 2**). Thus, their cycling  
305 mode share appears more sensitive to expansions of the cycling network (**Table 3**).

306

307 London, Rome and Barcelona are expected to benefit most in absolute and standardized  
308 terms in the all-streets (S4) scenario. These three cities: (1) have larger populations; (2)  
309 benefit particularly from the large absolute increase in cycling mode share (i.e. 3%, 1%  
310 and 2% at baseline, respectively (**Table 3**); and (3) benefit greatly from the estimated  
311 large increases in PA [i.e. PA levels were lowest at baseline (**Tables S.4-S.10**)].  
312 Generally, the cities baseline levels of PA, air pollution and traffic fatalities impact  
313 benefit estimations significantly (Rojas-Rueda et al., 2016; Tainio et al., 2016). Health  
314 benefits will be largest if at baseline the population is less physically active (and has  
315 high incidence rates for non-communicable diseases), air pollution levels are lower and  
316 traffic fatalities occur less. Despite health equity commonly being a subsidiary factor in  
317 the transport calculus, transport policies strongly determine the access to and use of the  
318 different modes of transport and thus their social significance and associated (often  
319 unequal) health pathway exposure distribution. As demonstrated in the sensitivity

320 analysis, the greatest health benefits occur by getting people out of their own cars,  
321 because public transport provides health benefits through implied PA (i.e. 10 minute  
322 walk) (Rojas-Rueda et al., 2012), and by being the safest mode of transport (Mueller et  
323 al., 2015). Hence, the parallel implementation of ‘push’ (e.g. making cars unattractive)  
324 and ‘pull’ (e.g. cycling network expansions) policies that consider equity impacts may  
325 best cater to adopt healthy transport behaviors, resulting in the largest benefits.

326

327 Policy implications of our findings may be – also under consideration of the supportive  
328 literature – that expansions of cycling networks may increase cycling, therefore,  
329 contributing to global health promotion and meeting sustainable development goals  
330 (United Nations, 2015). While other research also provides insight on ‘where’ cycling  
331 infrastructure should be located (e.g. the propensity to cycle tool) (Lovelace et al., 2016)  
332 and ‘how it should best look like’ (Mertens et al., 2016b), we simply like to express  
333 ‘that’ cycling networks should be high up on the agendas of city governments which  
334 have direct local accountability for providing ‘healthy choices’ to their citizens.  
335 Especially in cities with a low cycling mode share (i.e. Rome, Barcelona, London,  
336 Zurich and Vienna), already a 10% increase in cycling network length, which we  
337 perceive as an achievable policy for city governments, was estimated to provide  
338 considerable health and economic benefits.

339

#### 340 **4.1 Limitations and strengths**

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

345 invest in cycling infrastructure might already be congenial places for cycling. Data on  
346 other built-environment, transport and socio-economic factors that were shown to  
347 influence cycling [e.g. mixed land-use, street density and connectivity, gasoline prices,  
348 traffic safety, students among the population, urban greenery, etc. (Beenackers et al.,  
349 2012; Buehler and Pucher, 2012; Heesch et al., 2015; Sallis et al., 2015)] were not  
350 available, however, are expected to alter variability in cycling mode share considerably.

351

352 As with most HIAs, our analyses were limited by data availability and assumptions on  
353 causal inferences. Benefit estimations are sensitive to the contextual setting and  
354 underlying population and exposure parameters. Moreover, we considered exclusively  
355 the impacts for the actively traveling person. Societal co-benefits of reduced air and  
356 noise pollution (Buekers et al., 2015; Mueller et al., 2017b), reduced greenhouse gas  
357 emissions (Woodcock et al., 2009), and improved social cohesion and mental health  
358 (Litman, 2016a, 2016b) are expected with reductions in motor traffic and increases in  
359 active transport. Also, quality of life or morbidity impacts have not been considered, but  
360 are expected to be considerable (Mueller et al., 2017a). Additionally, we did not stratify  
361 our impact estimations by age, sex, or socioeconomic status even though benefit  
362 variations thereof are expected (Mueller et al., 2015). Finally, the presented cost-benefit  
363 estimations should be regarded as a robust overall estimate of which investments in  
364 infrastructure will be offset by health benefits in the long-term. The chosen Dutch cost  
365 estimates, despite considering the reconstruction of roads, may overestimate elsewhere;  
366 also the VoSL is country-specific, which will result in differing cost-benefit ratios in  
367 other settings.

368

369 Strengths of this analysis include the novelty of being the first study to look holistically  
370 into the associations between cycling network, cycling mode share and associated health  
371 impacts across European cities. Using open-access OSM data, which for cycling  
372 infrastructure has been described of fairly good quality (Hochmair et al., 2013), and  
373 applying the same standardized data extraction method (Salmon and Mueller, 2017) add  
374 strength and ensure reproducibility.

375

## 376 **5. CONCLUSIONS**

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

380

381

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390

391 **CONFLICT OF INTEREST**

392 None.

393

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400

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