

Health Impacts of Bike Sharing Systems in Europe.

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Abstract

Background: Bike-sharing systems (BSS) have been implemented in several cities around the world as policies to mitigate climate change, reduce traffic congestion, and promote physical activity. This study aims to assess the health impacts (risks and benefits) of major BSS in Europe.

Methods: We performed a health impact assessment study to quantify the health risks and benefits of car trips substitution by bikes trips (regular-bikes and/or electric-bikes) from European BSS with more than 2000 bikes. Four scenarios were created to estimate the annual expected number of deaths (increasing or reduced) due to physical activity, road traffic fatalities, and air pollution. A quantitative model was built using data from transport and health surveys and environmental and traffic safety records. The study population was BSS users between 18 to 64 years old.

Results: Twelve BSS were included in the analysis. In all scenarios and cities, the health benefits of physical activity outweighed the health risk of traffic fatalities and air pollution. It was estimated that 5.17 (95%CI: 3.11-7.01) annual deaths are avoided in the twelve BSS, with the actual level of car trip substitution, corresponding to an annual saving of 18 million of Euros. If all BSS trips replaced car trips, 73.25 deaths could be avoided each year (225 million Euros saving) in the twelve cities.

Conclusions: The twelve major Bike-sharing systems in Europe provide health and economic benefits. The promotion of shifting car drivers to use BSS can significantly increase the health benefits. BSS in Europe can be used as a tool for health promotion and prevention.

1. Introduction

Motorized vehicles help the transportation of people and goods, stimulating the economy. However, the increasing use of motorized transport is also negatively influencing people's health and the environment due to high levels of pollution and traffic incidents (Khreis et al. 2016). Motorized vehicles are one of the major sources of environmental pollution and noise in urban areas (Schwela et al. 2008). About 70% of environmental pollution and 40% of greenhouse gas emissions in European cities comes from motorized transport (European Environment Agency 2010).

Several international organizations have requested the implementation of public policies to increase the use of active transport, such as walking or cycling, and public transport in order to reduce car use in urban areas, reducing greenhouse gas emissions, climate change impacts, encouraging physical activity and traffic safety (Dora and Phillips 2000; Kim and Dumitrescu 2010).

Bike-sharing systems (BSS) have been implemented in several cities around the world as policies to mitigate climate change, reduce traffic congestion, and promote physical activity. A bike-sharing system or bike-share scheme is a service in which bikes are made available for shared use to individuals on a very short-term basis. BSS allow people to borrow a bike from one point and return it to a different point. BSS has become very popular in cities across Europe, Asia and America, and in 2013 more than 500 BSS were implemented around the world (Larsen 2013). The first bike share began in Europe in 1965, and the first large-scale bike-sharing program was launched in 1995, in Copenhagen as *Bycyklen* (City Bikes) with 1100 bikes (Shaheen et al. 2010). Currently the BSS in Paris called “Vélib”, is the biggest in Europe with 23600 bikes and 1800 stations; other BSS have also reached a considerable large size as London (12000 bikes), Barcelona (6000), Lyon (4000) or Valencia, Seville, Milan or Brussels with more than 2000 bikes. In some countries like Spain, there has been a rapid increase in the number of BSS, almost doubling the number of systems implemented from 58 to 97 between 2008 and 2009. Currently, the world's largest systems are in China, in the cities of Hangzhou and Wuhan, with 90000 and 70000 bikes, respectively (Oortwijn 2015). Recently new BSS's have also introduced electric-bikes in their systems as part of the bicycle fleet

Previous studies have estimated the health risks and benefits of replacing the car trips by bike trips from BSS's in Barcelona (Rojas-Rueda et al. 2011) and London (Woodcock et al. 2014). These two previous studies have found that health benefits (from physical activity) can outweigh health risks (from traffic incidents and air pollution inhalation). Until now a comprehensive analysis of the health implication of multiple BSS has not

been performed. Neither, any of the previous studies have included electric-bicycles in their assessments. This study aims to assess the health impacts (in travelers) of major BSS's across Europe, describing the differences between cities according to their travel and BSS characteristics, levels of air pollution and traffic safety. This study also includes, for the first time, the assessment of health risks and benefits related to the introduction of electric-bikes in BSS's.

2. Methods:

2.1. Framework and BSS selection

We used a health impact assessment (HIA) approach to quantify the health risk and benefits of car trips substitution by bikes trips from European BSS with more than 2000 bikes. The estimated health outcome was the annual expected number of deaths (increased or avoided) due to physical activity, road traffic fatalities and air pollution (particulate matter less than 2.5 micrometers (PM_{2.5})) due to car trips substitution for BSS trips (figure 1). The analysis was focused only on BSS with more than 2000 bikes (bikes and/or e-bikes) in cities of the European Union of 28 countries (table 1). This selection criterion was based on the assumption that the larger BSS would impact larger populations, and will have a greater (temporal and political) stability to produce a long-term usability and impacts. London, UK, BSS was excluded from the analysis because a recent assessment has been performed (Woodcock et al. 2014). Barcelona, Spain, BSS was included in the analysis in spite of existing a previous assessment (Rojas-Rueda et al. 2011) because of its recent expansion, introducing e-bikes in the system and this expansion has not been considered in the previous assessment. Another European BSS's like the case of Strasbourg or Grenoble were not included in the analysis, although they met the inclusion criteria of more than 2000 bikes because it was not possible to access the data (number of trips, distance, duration, etc.) required to perform the assessment.

2.2. Scenarios and input data

Four scenarios were created to assess the health impacts of shifting from car to BSS bikes: the first scenario was focused on the observed (reported by a travel survey performed by each BSS) car substitution by BSS bike trips in the 12 cities (see supplemental material); the other three scenarios were focused on assumptions to assess "what if" the cars substitution would be larger for the 12 BSS (table 2). Scenario 1) the car trip substitution (by BSS trips) used in this scenario was the minimum percentage reported by each city (for those cities that have not reported the percentage of car trip substitution, was applied the minimum reported (4.7%) between the 12 cities); scenario 2) what if the car trip substitution (by BSS) was the maximum

reported (12%) in the 12 European cities; scenario 3) what if 50% of all BSS trips come from car trips; and 4) what if 100% of all BSS trips would come from car trips (see supplemental material). These last three scenarios (2,3 and 4) were aimed to show the potential of the BSS if higher levels of car trip substitution could be achieved.

The input data used for the analysis was obtained from official records on transport (travel surveys and/or travel counts), health (health surveys, traffic safety, and health statistics) and air quality database (World Health Organization database of air quality (Ambient Air Pollution Database, WHO 2016)). BSS data was obtained from a combination of data sources provided directly by the BSS management companies, official city records, and travel surveys (see supplemental material).

2.3. Quantitative model

A comparative risk assessment approach was followed to estimate the number of mortality cases related to each health determinant (physical activity, air pollution, and traffic incidents) (Perez L and Kunzli N 2009; World Health Organization 2008) (figure 1). The “TAPAS tool” developed and used in previous HIAs (Rojas-Rueda et al. 2012, 2016) was used to estimate the health impacts in this study. The TAPAS tool methods description has been reported elsewhere (Rojas-Rueda et al. 2012, 2016). The dose-response functions (DRF) used in the TAPAS tool, between physical activity, air pollution, and all-cause mortality, were selected from meta-analyses. The risk estimates from traffic fatalities by kilometer traveled were collected from health and transport statistics from each city. Exposure levels of each health determinant were estimated for each city and scenario. We estimated a relative risk of all-cause mortality and each health determinant by scenario, and the city following the risk assessment approach, and translated this into a population attributable fraction. Using the mortality rate in each country and the attributable fraction in each scenario and city, we estimated the number of deaths attributable to each scenario, city, and health determinant (Rojas-Rueda et al. 2011, 2016). The number of expected deaths was estimated only for individuals between 16 and 64 years (similar to the populations included in the DRF).

2.3.1. Physical Activity model

The physical activity exposure was estimated based on the trip duration, trip frequency, and physical activity intensity, using metabolic equivalent of task (MET). The physical activity was defined as 6.8 METs for bikes, 6.12 METs for e-bikes using “standard assistance”, and 2 METs for car travelers (Ainsworth et al. 2011; Gojanovic

et al. 2011; Louis et al. 2012; Simons et al. 2009) (see supplemental material). A sensitivity analysis was also performed assuming e-bike “high assistance” mode, defined as 5.4 METs. The relative risk of all-cause mortality was based on the DRF provided by a meta-analysis (Woodcock et al. 2011), assuming a non-linear DRF. The physical activity assessment takes into account the basal levels of physical activity in each population (country) to estimate a relative risk for each scenario before to be translated into a populational attributable fraction and estimate mortality cases (see supplemental material).

2.3.2. Air Pollution model

The air pollution assessment focused only on the exposure to particulate matter with a diameter less than 2.5 μm ($\text{PM}_{2.5}$), which has shown strong association with all-cause mortality (Laden et al. 2000; Pope 2007; Wichmann et al. 2000). We identified the annual average concentration of $\text{PM}_{2.5}$ in each city, using the World Health Organization database of air quality (Ambient Air Pollution Database, WHO 2016) (see supplemental material). We estimated the concentration of $\text{PM}_{2.5}$ in each microenvironment (bike and car), using background/car or bike ratios provided by previous meta-analysis (de Nazelle et al. 2017), following a similar approach as reported in previous studies (Rojas-Rueda et al. 2013, 2011, 2016). The inhaled dose was estimated using the minute ventilation according to the intensity of physical activity (in METs) in each mode of transport (bike, e-bike, and car), $\text{PM}_{2.5}$ concentration in the mode of transport and trip duration (Rojas-Rueda et al. 2013, 2011, 2016). The DRF for $\text{PM}_{2.5}$ and all-cause mortality from a meta-analysis was used (RR = 1.06 (1.04, 1.08)) for each increment of 10 $\mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$) (Hoek et al. 2013). Finally using the comparative risk assessment approach, we estimated the relative risk, attributable fraction, and expected deaths for each scenario, and city (see supplemental material).

2.3.3. Road Traffic model

Road traffic fatalities in each scenario and city were estimated using the traffic fatalities reported in each city and mode of transport (using traffic fatalities per billion of kilometers traveled)(see supplemental material). For each scenario and city we estimated the number of kilometers traveled by car, bike, and e-bike. The expected traffic fatalities by mode of transport were estimated using the traffic fatalities per billion of kilometer traveled and the distance traveled in each mode of transport and city (Hartog et al. 2010; Rojas-Rueda et al. 2011). Then was calculated a relative risk of mortality in a road traffic crash for cyclists (regular-bike or e-bike) compared with car drivers. The relative risk was translated to an attributable fraction and to a final number of fatality cases in each scenario (see supplemental material).

2.3.4. Economic assessment

An economic assessment was included using the value of statistical life for each country reported by the Organization for Economic Co-operation and Development (OECD 2012). The estimated deaths in each city and scenario were multiplied to the value of statistical life of their corresponding county and calculated the economic values, following the methods proposed by World Health Organization in the Health economic assessment tool for cycling (Kahlmeier et al. 2014).

2.3.5. Electric bikes (E-bikes)

The TAPAS tool was developed for regular-bikes, for this reason in this assessment we updated the TAPAS tool to include e-bikes. The e-bike update was focused on including specific values for physical activity(METs), speed, traffic fatalities rates(for kilometers traveled) and inhalation rates for e-bikes(see supplemental material).

A specific analysis of e-bikes was also performed distinguishing two different types of e-bikes, “standard assistance” e-bikes, and “high-assistance” e-bikes (see supplemental material). For each of those type of e-bikes we selected different physical activity levels (METs) and speed. The “standard assistance” e-bike was used as a common reference in all scenarios, and the “high assistance” e-bike was used for sensitivity analysis. In terms of physical activity, “standard assistance” e-bikes was defined as an e-bike that requires 90% of the physical activity of a regular-bike, and “high assistance” e-bike was defined as an e-bike that requires 75% of the physical activity of a regular-bike (Gojanovic et al. 2011; Louis et al. 2012; Simons et al. 2009). In terms of speed, “standard assistance” e-bikes were defined as an e-bike that increases in average 21% the speed of a regular-bike, and “high assistance” e-bike was defined as an e-bike that increases on average 33% the speed of a regular-bike (Gojanovic et al. 2011; Simons et al. 2009). For traffic fatalities, e-bikes were assumed to have an odds ratio of 1.92 (1.48-2.48) compared with a regular-bike as proposed by Schepers et al. (Schepers et al. 2014).

3. Results

Twelve BSS were included in the analysis, nine BSS with regular-bikes (Brussels, Hamburg, Lille, Lyon, Paris, Seville, Toulouse, Valencia, and Warsaw), two with regular-bikes and e-bikes (Barcelona and Milan) and one BSS with only e-bikes (Madrid). The

number of bikes in the BSS ranged between 2200 in Lille, and 23600 in Paris. The BSS trips per day range from 4320 in Brussels to 11000 in Paris. The number of trips per day by bike range from 0,9 daily trips per bike in Brussels to 11,3 daily trips per bike in Valencia. In all the cases (cities and scenarios), the health benefits of physical activity outweighed the health risk of traffic fatalities and inhalation of air pollution (figure 2).

3.1 Scenario 1. Minimum observed car trips substitution

In the scenario 1, we estimated that 5.17 (95%CI: 7.01-3.11) deaths are avoided each year corresponding to 18.1 million Euros (95%CI: 31.5-12.4) (table 3) when the twelve systems are added up. The city with the highest estimated benefits was Paris with 2.53 deaths avoided per year and 10 million Euros, followed by Barcelona with 0.80 annual deaths avoided per year and 2.5 million Euros. The BSS with the fewest deaths avoided were Brussels, Madrid, and Lille with less than 0.07 annual deaths avoided within each city. The estimation of deaths avoided per 1000 bikes ranged from 0,01 deaths avoided per year in Brussels per every 1000 bikes to 0,13 deaths annual avoided per every 1000 bikes in Barcelona, with an average of 0,07 deaths avoided per year by 1000 bikes between the twelve BSS's.

3.2 Scenario 2. The 12% of the BSS trips come from car trips

For scenario 2 if 12% (maximum reported car trips substitution) of the BSS trips come from car trips, we estimated that 8.79 (95%CI: 11.97-5.30) deaths would be avoided each year corresponding to 39.3 million Euros (95%CI: 48.5-21.5) for the twelve systems together and. The city with the highest estimated benefits was Paris with 3.80 deaths avoided per year and 15.2 million Euros saved. The BSS with the fewest deaths avoided were Brussels, Madrid, and Hamburg with less than 0.13 annual deaths avoided in each city.

3.3 Scenario 3. The 50% of the BSS trips come from car trips

In the scenario 3 if 50% of BSS trips come from car trips, we estimated that 36.6 (95%CI: 49.90-22.07) deaths would be avoided each year corresponding to 112.9 million Euros (95%CI: 186.5-89.3) for all twelve systems together. The city with highest benefits would be Paris with 15.85 deaths avoided per year and 63.5 million Euros. The BSS's with fewer deaths avoided would be Brussels, Madrid, and Hamburg with less than 0.60 annual deaths avoided in each city.

3.4 Scenario 4. The 100% of the BSS trips come from car trips

In the scenario 4 if the 100% of the BSS trips come from car trips, we estimated that 73.25 (95%CI: 99.81-44.14) deaths would be avoided each year and 225.9 million Euros saved (95%CI: 404-1178) for the twelve systems together. The city with the highest benefits would be Paris with 31.70 deaths avoided per year and 126.9 million Euros saved. The BSS with the fewest deaths avoided would be Brussels, Madrid, and Hamburg with less than 1.20 annual deaths avoided in each city.

4. Discussion

This is the first study assessing the health impacts of multiple bike-sharing systems in Europe. This study included the 12 larger BSS in Europe, in six different countries (Belgium, France, Germany, Italy, Poland and Spain). This is also the first health impact assessment of e-bikes. BSS's have increased and become popular around the world in recent years. This study provided a systematic assessment comparing different BSS's across Europe.

This study found that the 12 larger European BSS could prevent up to 73 deaths each year with an economic value of 225 million Euros if 100% of BSS trips were replacing car trips. In the most conservative scenario (minimum reported car trips substitution), we estimated that each year 5 deaths could be prevented by the 12 BSS systems in Europe, with an economic value of more than 18 million Euros. In all the cities and scenarios assessed the health benefits outweighed the health risks with a benefit/risk ratio of 19:1 (see supplemental material). The benefits are mainly driven by the increase in physical activity derived from the use of the bike or e-bikes as a means of daily transportation.

In this study, we found that health impacts vary among BSS's and cities. Using the most conservative scenario (scenario 1 "minimum reported car trips substitution), was estimated the annual deaths avoided per 1000 bikes (table 2), resulting in a range of 0,01 annual deaths avoided per 1000 bikes in Brussels to 0,13 deaths avoided per 1000 bikes in Barcelona. This variability in the health impacts of the same amount of bikes can be explained because each BSS have different usability ratio (number of daily trips per bike)(see table 1), different trip duration, traffic safety and air quality. If the local authorities work to improve those factors (bike usability rate, traffic safety, and air quality) the potential health benefits of current BSS's could be greater. Similar to this analysis, an estimation of the future increment of BSS trips or users (new cyclist) was estimated assuming that these new trips and new cyclists come from car trips (table

2). If the BSS increase by 1000 trips per day, the health benefits could be translated into 0,15 annual deaths avoided in Milan or Madrid to 0,39 in Warsaw. If the BSS increase by 1000 new cyclist, the health benefits could be translated into 0,55 deaths per year in Madrid to 1.40 in Warsaw. In the case of scenario 3 and 4 where most of the BSS trips are assumed to come from car trips, we acknowledge that these are unrealistic, but provide a sense of the magnitude of health impacts in the best case scenarios.

Vélib' the BSS in Paris was the system with the largest health benefits compared with the other European cities. This can be explained because it is the largest system in Europe, with more than 23 thousand bikes and 110 000 trips per day, representing 2.04% of total trips made in the urban area of Paris. Also, Paris has a high car trip substitution of BSS trips (8.0%) that is almost the double of the reported in other cities like Seville (4.7%). Furthermore, Paris trips have longer distances (3.3 km) compared to the average of the rest of the cities (2.92 km)(see supplemental material). Lille, Madrid, and Brussels were the cities where the estimated health benefits were lower compared to the rest of cities included. These three cities were characterized by having a small bike fleets (between 2028 to 5000 bikes) and the lowest number of daily trips (between 4320 to 7900).

Madrid was the only BSS composed to 100% by e-bikes, which were related to lower physical activity, higher speed, and traffic incidents and produced overall fewer health benefits than a BSS with regular-bikes. Barcelona and Milan also have a BBS's with a mix of regular-bikes and e-bikes. The impacts produced only by the e-bikes in the three cities varied significantly (annual death avoided: Madrid 1, Milan 0.3, and Barcelona 0.05)(in scenario 4). This can be explained because the number of e-bikes in each city is also different (number of e-bikes: Madrid 2028, Milan 1000, and Barcelona 300). In these three cities, the e-bikes were analyzed assuming a "standard assistant" mode, which was defined as 6.5 METs of physical activity compared to a regular-bike (7 METs)(see supplemental material). We also performed a sensitivity analysis assumed a "high assistance" mode of e-bikes, assuming 5.4 METs. In this sensitivity analysis, we still found health benefits in the three BSS's (Barcelona, Madrid, and Milan) in spite of the increased risk of traffic fatalities and lower levels of physical activity. Although the health benefits of e-bikes are lower than regular-bikes, the availability of e-bikes can attract a new group of bike users (i.e., older people) or the substitution of longer or hillier trips. Unfortunately, these considerations were not taken into account in this analysis due to the lack of information about the e-bike users and route characteristics in the cities. Some cities like Lyon (Crouzet 2017) are planning to introduce e-bikes in the future to deal with hilliness and attracting more users (as made by Barcelona, Madrid, and Milan). For that reason, it will be important to improve BSS data collection

(i.e., travel surveys) with special attention describing user's characteristics and route preferences.

Physical activity provides the largest health impacts in this analysis. Physical exercise prevents cardiovascular diseases, reduces the risk of diabetes mellitus, certain cancers, and mortality (Rojas-Rueda et al. 2013). This study only included as health outcome all-cause mortality (for physical activity, air pollution, and traffic incidents), because it was expected to be the health outcome with the largest health and economic impacts (Rojas-Rueda et al. 2013). This assessment was performed using the TAPAS tool for cycling; this tool has been used in previous active transportation assessments (Rojas-Rueda et al. 2012, 2013, 2011, 2016). The TAPAS tool for cycling estimates the physical activity health benefits using a non-linear DRF, considering the basal level of physical activity in the population under assessment (Woodcock et al. 2014). This approach takes into account that those who already were physically active would gain fewer benefits compared to those that are more sedentary. This non-linear approach results in fewer health benefits from physical activity than using a linear model (Rojas-Rueda et al. 2016).

The air pollution assessment in this study only considered the health risk associated with the inhalation of PM_{2.5} during the bike trip (Rojas-Rueda et al. 2016). Other changes in air pollution exposure, associated to car-bike substitution at the city level, were not included in this study. Although, additional co-benefits could be expected on air quality associated with car trip substitution. This study only focused on PM_{2.5}, although other pollutants, (e.g. NO₂ or black carbon), could also be used in this type of assessments. These pollutants are highly correlated and produce similar health outcomes. In order to avoid double counting in the air pollution model, we decided to include only PM_{2.5}. This study found differences in the air pollution exposure among cities. These differences can be explained by the PM_{2.5} concentrations at the city level, trip duration and frequency, and the intensity of physical activity (regular-bikes, e-bikes standard or high assisted). In all the cities and scenarios, the air pollution was found as a risk factor for cycling. Compared with the other health determinants included in the analysis, air pollution was the one with fewer health impacts (figure 2). The cities that had the worst levels of air pollution (PM_{2.5}) were Milan (30 µg/m³) and Warsaw (26 µg/m³), but none of the cities assessed had levels under the World Health Organization recommendations (<10 µg/m³) (WHO 2006). If the cities improve the air pollution levels, the overall health benefits of the BSS could be bigger. The car-bike substitution could also produce a reduction in air pollution emissions and concentrations, bringing health benefits to the general population, but these impacts were not in the scope of this study.

The traffic incident model estimates the risk of traffic fatalities per kilometer traveled. The risk of kilometer traveled was obtained from the health and transport records from each city (see supplemental material). Traffic fatalities can be influenced by multiple causes, traveler behavior, infrastructure, traffic laws, and mode of transport. This study took into account the risk of the mode of transport (car, bike or e-bike), but did not assess the different impacts related to age, sex, or route due to the lack of information on these characteristics in the traffic safety records of each city. In all the cities (with the exception of Seville) we found that car-bike substitution increases the risk of traffic fatalities in the travelers (see figure 2). Milan, Brussels, and Warsaw provided the highest risk of traffic fatality between cities when the car is substituted by bike. Seville is the only city that reported a lower risk of traffic fatalities in bike compared to a car. This can be explained because in the last few years Seville has invested in bike infrastructure, especially in segregated bike lanes, traffic signaling, and bike promotion and education (Ayuntamiento de Sevilla 2007; Junta de Andalucía 2014).

The results of this study agree with the findings from previous publications, (Rojas-Rueda et al. 2011) that performed a HIA on the BSS of Barcelona, including the same health determinants (physical activity, air pollution, and traffic incidents). Unlike this previous Barcelona assessment, our study included an update of the TAPAS model, introducing a non-linear DRF for physical activity, different car-bike substitution scenarios, update DRF for air pollution, and the e-bikes assessment. Our study estimates a range of 0.8 to 8 deaths avoided each year in Barcelona, compared to the 12 deaths avoided as estimated in the previous study. This difference can be explained because of the different scenarios that were used in the studies and the inclusion of a non-linear DRF for physical activity in this new analysis. Woodcock J et al. (2014) (Woodcock et al. 2014) also performed a health impact modeling study of the BSS in London, finding health benefits associated with the use of the BSS.

This study was focused only on measuring the health impacts of car trip substitution by BSS trips. This choice was justified because the car trips substitution was suggested to provide more health benefits (compared to other transport modes). A previous health impact assessment compared the potential benefits of shifting from different transport modes (car, public transport, and walking) to bike (Rojas-Rueda et al., 2016). This assessment found that car-bike substitution provided the highest health benefits (Rojas-Rueda et al., 2016). Furthermore, car-bike substitution also brings co-benefits at the city level, improving traffic noise, air quality, traffic safety, emissions of greenhouse gases, and the use of public space, among others.

As in all risk assessments, our study was limited by the availability of data and the necessity to make assumptions to model likely scenarios. In terms of the scenarios modeled a conservative scenario (scenario 1) was created using data from travel surveys knowing the current car-bike substitution between the BSS users. In the case of lack of data on car-bike substitution, we assumed a conservative shift using the minimum car-bike substitution reported between the 12 cities (4.7%). The other scenarios ("what if" scenarios) showed the actual potential of the BSS to improve health. That is especially relevant considering that the BSS already exist in those cities, and if more actions could be taken to promote car-bike substitution (through media campaigns, education, economic incentives, urban infrastructure and transport planning improvements) higher health and economic benefits could be achieved by the BSS. One limitation was the definition of e-bikes, because there exists different type of e-bikes, plus e-bike users also can choose different level assistance when they use the e-bikes. To assess the different possibilities of types and use of e-bikes, we defined two different levels of assistance in our analysis, "standard assistance" used in the main analysis and "high assistance" used as a sensitivity analysis. An important part of the work performed in this study was data collection, for that reason the BSS managers were contacted directly by the researchers to collect the information from each BSS and city. For this reason, a survey was performed to collect systematically the data required in the analysis. When BSS managers reported the absence of data, the BSS was excluded from the analysis. This happened for the BSS of Strasbourg or Grenoble. Finally, if the majority of the data was available, but still data missing, the missing data were estimated using a secondary analysis (crossover analysis) using data from other BSS or cities. To assess the uncertainty in our estimates confidence intervals were included. The confidence intervals were composed by the variability of the input data, using the ranges (maximum and minimum) and the confidence intervals from the DRF from physical activity and air pollution.

Some general recommendations can be derived from the actual study to different stakeholders and researchers. For the BBS managers and transport authorities it is recommended to systematically collect data about the BSS's (number of trips, frequency, and duration, user characteristics, routes, etc.), also to harmonize data between BBS and cities, and the publication of the BSS data (in a free and open access formats). For local authorities, it is recommended to provide and collect harmonize traffic safety data for different mode of transports (including BSS) between European cities. In terms of research it is important to obtain more evidence on e-bikes, characterizing better the type of e-bikes available in the BSS, levels of assistance in the e-bikes, e-bike trips description (route, duration, speed, type of user), e-bikes traffic safety data across Europe, and a better definition of the physical activity related to the different types of e-bikes. Also, new data sources on physical activity and

transportation are available from crowdsourced databases (Afzalan and Sanchez 2017; Oates et al. 2017; Sun and Mobasher 2017; Sun et al. 2017). These new databases can provide relevant information to understand cyclist behaviors, routes, exposures, among others, and better inform policymakers.

5. Conclusions

This study found that BSS in Europe can provide health and economic benefits. The health benefits are driven by physical activity, with minor risks due to exposure to air pollution (PM_{2.5}) and road traffic fatalities. The health impacts of the BSS differ across European cities depending on the car-bike substitution level, traffic safety, and air quality. This study also included e-bikes, which were found to provide less health and economic benefits in BSS's than regular-bikes. The promotion of BSS use among car drivers can significantly increase the health, and economic benefits of BSS and BSS can be used as a tool for health promotion and prevention.

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Table 1. Description of 12 European bike sharing systems (BSS) included in the analysis.

City	City population (inhabitants)	Bike sharing system name	Type of bicycle	Number of regular-bikes	Number of E-bikes	BSS trips per day	Bike usability ratio (daily trips/bike)	Year of implementation	Operator
Barcelona	1 604 555	Bicing	Bike & E-bike	6 000	300	38 946	6,2	2007	Clear Channel
Brussels	1 187 890	Villo	Bike	5 000	-	4 320	0,9	2009	JCDecaux-Cyclocity
Hamburg	1 787 408	StadtRAD Hamburg	Bike	2 450	-	6 671	2,7	2009	Deutsche Bahn <i>"Call a Bike"</i>
Lille	233 897	V'Lille	Bike	2 200	-	7 900	3,6	2011	Kéolis
Lyon	506 615	Vélo'v	Bike	4 000	-	30 000	7,5	2005	JCDecaux - Cyclocity
Madrid	3 165 883	BiciMAD	E-bike	-	2028	6 935	3,4	2014	Bonopark S.L.
Milan	1 345 851	BikeMi	Bike & E-bike	3 650	1000	17 700	3,8	2008	Clear Channel
Paris	2 273 305	Vélib'	Bike	23 600	-	110 000	4,7	2007	JCDecaux - SOMUPI
Seville	690 566	Sevici	Bike	2 500	-	11 618	4,6	2007	JC Decaux-Cyclocity
Toulouse	466 297	Vélô	Bike	2 600	-	13 000	5,0	2007	JC Decaux-Cyclocity
Valencia	787 266	Valenbisi	Bike	2 700	-	30 560	11,3	2010	JC Decaux-Cyclocity
Warsaw	1 748 900	Veturilo	Bike	4 925	-	21 333	4,3	2012	Nextbike Polska

E-bike: Electric bicycle.

Table 2. Results of the 12 European bike sharing systems (BSS) by scenario, in annual deaths avoided.

BSS by city	Observed substitution		What if...				
	Scenario 1		Scenario 2	Scenario 3	Scenario 4	Increase 10 000 BSS trips per day	Increase 1000 cyclists per day
	Minimum observed car trips substitution	Deaths avoided per 1000 bikes	12% of BSS trips come from car trips ^a	50% of BSS trips come from car trips	100% of BSS trips come from car trips		
	<i>deaths /year (95% CI)</i>	<i>deaths/year</i>	<i>deaths /year (95% CI)</i>	<i>deaths /year (95% CI)</i>	<i>deaths /year (95% CI)</i>	<i>deaths /year (95% CI)</i>	<i>deaths /year (95% CI)</i>
Barcelona	-0.80 (-1.03, -0.47)	-0.13	-1.00 (-1.29, -0.59)	-4.18 (-5.38, -2.46)	-8.37 (-10.76, -4.92)	-2.13 (-2.74, -1.25)	-1.27 (-1.65, -0.65)
Brussels	-0.07 (-0.10, -0.03)	-0.01	-0.12 (-0.17, -0.06)	-0.52 (-0.73, -0.25)	-1.04 (-1.46, -0.51)	-2.41 (-3.8, -1.19)	-0.85 (-1.19, -0.42)
Hamburg	-0.13 (-0.19, -0.08)	-0.05	-0.13 (-0.19, -0.07)	-0.55 (-0.80, -0.30)	-1.11 (-1.61, -0.59)	-1.66 (-2.41, -0.89)	-0.58 (-0.85, -0.31)
Lille	-0.07 (-0.09, -0.04)	-0.03	-0.17 (-0.23, -0.11)	-0.71 (-0.99, -0.47)	-1.43 (-1.98, -0.94)	-1.81 (-2.51, -1.19)	-0.72 (-1.00, -0.47)
Lyon	-0.48 (-0.68, -0.39)	-0.12	-0.81 (-1.17, -0.67)	-3.40 (-4.89, -2.79)	-6.80 (-9.78, -5.59)	-2.26 (-3.26, -1.86)	-0.74 (-1.07, -0.61)
Madrid	-0.07 (-0.09, -0.01)	-0.03	-0.13 (-0.18, -0.01)	-0.54 (-0.75, -0.06)	-1.09 (-1.50, -0.13)	-1.58 (-2.16, -0.19)	-0.55 (-0.76, 0.06)
Milan	-0.14 (-0.19, -0.07)	-0.03	-0.37 (-0.50, -0.17)	-1.54 (-2.09, -0.73)	-3.09 (-4.18, -1.46)	-1.54 (-2.08, -0.72)	-1.03 (-1.43, -0.39)
Paris	-2.54 (-3.38, -1.48)	-0.11	-3.80 (-5.07, -2.21)	-15.85 (-21.1, -9.22)	-31.70 (-42.28, -18.45)	-2.88 (-3.84, -1.67)	-0.98 (-1.30, -0.57)
Seville	-0.11 (-0.14, -0.06)	-0.04	-0.27 (-0.35, -0.15)	-1.13 (-1.49, -0.63)	-2.26 (-2.98, -1.27)	-1.94 (-2.57, -1.09)	-0.68 (-0.90, -0.38)
Toulouse	-0.13 (-0.17, -0.07)	-0.05	-0.32 (-0.45, -0.19)	-1.35 (-1.89, -0.79)	-2.71 (-3.78, -1.58)	-2.08 (-2.91, -1.21)	-0.79 (-1.10, -0.46)
Valencia	-0.24 (-0.33, -0.16)	-0.09	-0.61 (-0.84, -0.40)	-2.55 (-3.53, -1.66)	-5.10 (-7.06, -3.33)	-1.67 (-2.31, -1.09)	-0.59 (-0.81, -0.38)
Warsaw	-0.40 (-0.58, -0.25)	-0.08	-1.02 (-1.48, -0.63)	-4.25 (-6.19, -2.66)	-8.50 (-12.38, -5.32)	-3.98 (-5.807, -24.96)	-1.40 (-2.05, -0.88)
Total	-5.17 (-7.01, -3.11)	-0.07**	-8.79 (-11.97, -5.30)	-36.62 (-49.90, -22.07)	-73.25 (-99.80, -44.14)	-26.00 (-36.02, -14.90)	-10.24 (-14.17, -5.64)

BSS: Bikes sharing system; CI: Confidence intervals; ^a12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included; **Average deaths avoided per 1000 bikes between the 12 BSS.

Table 3. Results of the 12 European bike sharing systems (BSS) by scenario, in million Euros saved per year.

BSS by city	Observed substitution	What if...		
	Scenario 1 Minimum observed car trips substitution Million Euros /year (95% CI)	Scenario 2 12% of BSS trips come from car trips ^a Million Euros /year (95% CI)	Scenario 3 50% of BSS trips come from car trips Million Euros /year (95% CI)	Scenario 4 100% of BSS trips come from car trips Million Euros /year (95% CI)
Barcelona	2.571 (1.511. 3.311)	3.218 (1.892. 4.138)	13.407 (7.882. 17.241)	26.815 (15.761. 34.483)
Brussels	0.319 (0.157. 0.446)	0.547 (0.271. 0.766)	2.286 (1.125. 3.202)	4.573 (2.256. 6.404)
Hamburg	0.562 (0.330. 0.816)	0.562 (0.330. 0.816)	2.353 (1.269. 3.526)	4.706 (2.535. 6.814)
Lille	0.268 (0.176. 0.372)	0.688 (0.452. 0.957)	2.863 (1.890. 3.981)	5.731 (3.776. 7.962)
Lyon	1.906 (1.570. 2.743)	3.272 (2.687. 4.701)	13.629 (11.202. 19.584)	27.262 (22.400. 39.169)
Madrid	0.224 (0.025. 0.307)	0.422 (0.051. 0.576)	1.758 (0.211. 2.405)	3.513 (0.422. 4.810)
Milan	0.519 (0.245. 0.696)	1.319 (0.625. 1.785)	5.497 (2.609. 7.438)	10.998 (5.219. 14.877)
Paris	10.156 (5.911. 13.537)	15.235 (8.867. 20.321)	63.488 (36.947. 84.676)	126.977 (73.898. 169.352)
Seville	0.339 (0.192. 0.448)	0.871 (0.486. 1.146)	3.625 (2.033. 4.782)	7.251 (4.067. 9.564)
Toulouse	0.512 (0.300. 0.712)	1.305 (0.764. 1.818)	5.438 (3.180. 7.585)	10.877 (6.360. 15.167)
Valencia	0.768 (0.502. 1.063)	1.963 (1.284. 2.716)	8.177 (5.345. 11.319)	16.354 (10.691. 22.635)
Warsaw	2.351 (1.469. 3.421)	5.995 (3.756. 8.740)	24.994 (15.653. 36.409)	49.988 (31.307. 72.825)
Total	18.150 (12.393. 31.511)	39.320 (21.471. 48.486)	112.980 (89.352. 186.573)	225.962 (178.698. 404.066)

BSS: Bikes sharing system; CI: Confidence intervals; ^a12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included

Figure 1. Conceptual framework of bike sharing systems and health.

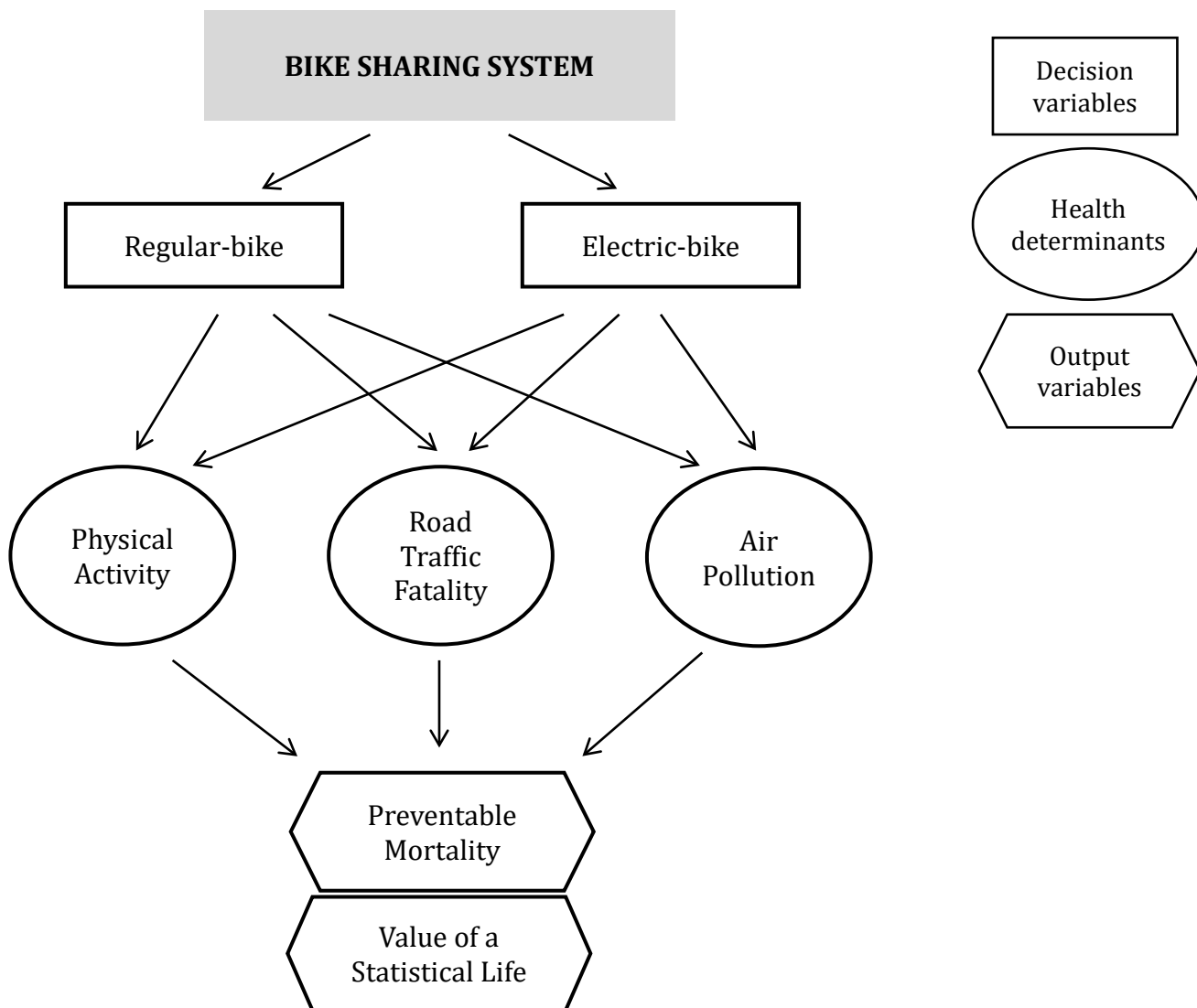
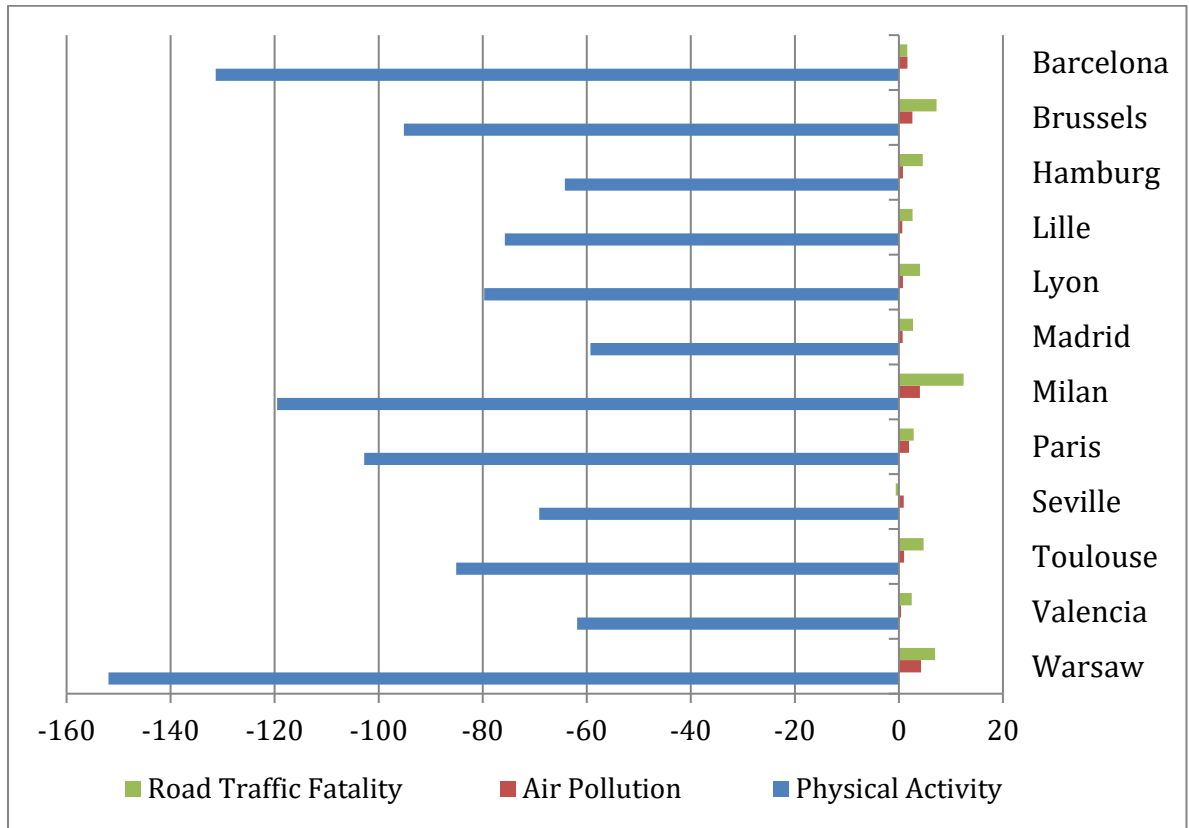


Figure 2. Number of annual deaths prevented per year per 100 000 cyclists, by health determinant, if 100% of BSS trips come from car trips (scenario 4).



Supplemental Material

Health Impacts of Bike Sharing Systems in Europe.

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Figure S4. Number of annual deaths prevented per year per 100 000 trips, by health determinant, if 100% bicycle trips will replace car trips (scenario 4). 32

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Section 1. Methods

Table S1. Trips per day by bike or E-bike, by scenario and city.

BSS by city	Bicycle type	BSS trips per day	Observed substitution		What if...	
			Scenario 1 Minimum observed car trips substitution <i>deaths /year (95% CI)</i>	Scenario 2 12% of BSS trips come from car trips ^a <i>deaths /year (95% CI)</i>	Scenario 3 50% of BSS trips come from car trips <i>deaths /year (95% CI)</i>	Scenario 4 100% of BSS trips come from car trips <i>deaths /year (95% CI)</i>
Barcelona	bike	38946	3738.8 (9.6)	4673.5	19473	38946
Barcelona	E-bike	277.3	26.6 (9.6)	33.3	138.6	277.3
Brussels	bike	4320	302.4 (7)	518.4	2160	4320
Hamburg	bike	6671	800.5 (12)	800.5	3335.5	6671
Lille	bike	7900	371.3 (4.7) ^b	948	3950	7900
Lyon	bike	30000	2100 (7)	3600	15000	30000
Madrid	E-bike	6935	443.8 (6.4)	832.2	3467.5	6935
Milan	bike	17700	831.9 (4.7) ^b	2124	8850	17700
Milan	E-bike	2300	108.1 (4.7) ^b	276	1150	2300
Paris	bike	110000	8800 (8)	13200	55000	23195
Seville	bike	11618	546.1 (4.7)	1394.2	5809	11618
Toulouse	bike	13000	611 (4.7) ^b	1560	6500	13000
Valencia	bike	30560	1436.3 (4.7)	3667.2	15280	30560
Warsaw	bike	21333	1003 (4.7) ^b	2559.9	10666.5	21333

BSS: Bike sharing system; CI: Confidence interval

^a 12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included.

^b Percentage assumed in reference to the minimum value obtained from substitution of mode of transport by car by the bicycle sharing systems.

Scenarios were built based on assumptions about the shifting modal distribution between car and bicycle share systems (BSS), this table shows the data with bike and E-bike.

Each scenario represents a percentage of car trips substitution by BSS bikes between the 12 European cities studied (if there was not BSS modality, the car would be used as a means of transport).

Table S2. Car and bike speed (km/h) in 12 European cities

These data have been used to calculate the mean, maximum and minimum to use in those cities without information on the average speed car and bicycle.

	Speed Car (km/h)	Speed Bike (km/h)
Barcelona	21.8	9.6
Brussels	20	10
Basel	25	11.6
Copenhagen	27	16
Lyon	15	13.5
Madrid	23.2	12
Milan	25.4	8.8
Paris	15	9.9
Prague	45	12
Toulouse	26	11
Warsaw	38	13.4
Average	19	11.6
Minimum	15	8.8
Maximum	45	13.5

References:

(Jensen et al. 2010)

(Massot et al. 2004)

(Pérez and Monzón 2011)

(Rojas-Rueda et al. 2016)

(Vander Linden and Colfs 2015)

Table S3. Car and bike traffic fatalities in 14 European cities.

These data have been used to calculate the mean, maximum and minimum to use in those cities without information on the traffic fatalities.

BSS by city	Car <i>Deaths per billion of kilometers traveled</i>	Bike <i>Deaths per billion of kilometers traveled</i>
Antwerp	2	14
Barcelona	3	5.92
Basel	0.79	5.63
Copenhagen	5.04	3.42
London	1	28
Madrid	2,72 ^a	6.08
Örebro	3	34
Paris	1.66	13.61
Prague	1.07	33.05
Rome	6	89.38
Strasbourg	8.62	40.79
Vienna	2	11
Warsaw	1.99	23.31
Zurich	0	18
Average	2.72	23.29
Minimum	0	3.42
Maximum	8.62	89.38

BSS: Bike sharing system

^a Input data used was taken from the average of the 14 cities.

References:

(Mueller 2017)

(Rojas-Rueda et al. 2016)

Table S4. Basal levels of physical activity (in METs) reported in European countries included in the analysis.

Basal level of physical activity (METs)^a	Group 1	Group 2	Group 3	Group 4
Belgium	2	10	32	0
France	5	17.5	25	0
Germany	7.5	18	50.4	0
Italy	2	5.97	10	0
Poland	0	38	58.2	0
Spain	2	5.97	10	20

Group refers to tertiles or quartiles depending of the data sources of each country.

^b METs/h/w: Metabolic equivalent of task per hour per week

References:

(Drieskens et al. 2013)

(Azienda Unita' Sanitaria Locale Roma D 2011)

(Bartoll et al. 2013)

(Rojas-Rueda et al. 2016)

Table S5. Type of e-bikes and Metabolic Equivalent of Tasks (METs).

Data used to calculate METs from the change of bike to E-bike, taking into account the values for standard assistance and high assistance.

	GOJANOVIC B, 2011 <i>METs</i>	SIMONS M, 2009 <i>METs</i>	LOUIS J, 2012 <i>METs</i>	Average (%) <i>METs</i>
Bike	8.2	6.1	7.5	7.2 (100)
E-Bike (standard assistance)	7.3	5.7	6.7	6.5 (90)
E-Bike (high assistance)	6.1	5.2	4.9	5.4 (75)

References:

(Gojanovic et al. 2011)

(Simons et al. 2009)

(Louis et al. 2012)

Table S6. Type of e-bikes and speed (km/h).

Data used to calculate speed from the change of bike to E-bike, taking into account the values for standard assistance and high assistance.

	GOJANOVIC B, 2011	SIMONS M, 2009	Average (%)
	<i>(km/h)</i>	<i>(km/h)</i>	<i>(km/h)</i>
Bike	10.3	19.6	14.9
E-Bike (standard assistance)	15.1	21.1	18.1 (+21)
E-Bike (high assistance)	16.5	23.4	19.9 (+33)

References:

(Gojanovic et al. 2011)

(Simons et al. 2009)

Table S7. Traffic fatality odds ratio for e-bikes.

Data used to calculate traffic fatalities from the change of bike to E-bike.

Odds Ratio (crashes)	Schepers J, 2014
Bike	1.00
E-Bike	1.92

Reference:

(Schepers et al. 2014)

Table S8. Input data used in the analysis for bikes(non-electric bikes).

BSS by city	Barcelona	Brussels	Hamburg	Lille	Lyon	Milan	Paris	Seville	Toulouse	Valencia	Warsaw
<i>Inhabitants</i>	1604555	1187890	1787408	233897	506615	1345851	2273305	690566	466297	787266	1748900
<i>Mortality rates 16-64 years (deaths /1000 inhab)</i>	2.05	2.30	1.67	2.28	2.28	1.74	2.73	2.06	2.28	2.01	3.70
<i>Air pollution average annual concentration (ug/m³)*</i>	15	18	14	17	14	30	18	16	12	11	26
<i>Traffic fatalities per billion of km traveled</i>	-	-	-	-	-	-	-	-	-	-	-
- <i>Bicycle (average)</i>	5.92	23	23	23	23	23	13.61	0.22	23	23	23.31
<i>Bicycle (LCI)^a</i>	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
<i>Bicycle (UCI)^b</i>	89.38	89.38	89.38	89.38	89.38	89.38	89.38	89.38	89.38	89.38	89.38
- <i>Car (average)</i>	3	3	3	3	3	3	1.66	3	3	3	1.99
<i>Car (LCI)^a</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Car (UCI)^b</i>	8.62	8.62	8.62	8.62	8.62	8.62	8.62	8.62	8.62	8.62	8.62

Continue from table S8.

BSS by city	Barcelona	Brussels	Hamburg	Lille	Lyon	Milan	Paris	Seville	Toulouse	Valencia	Warsaw
<i>Average trips per person/day</i>	3.10	3.53	3.53	4	3.30	3.53	3.40	3.53	3.80	3.53	3.53
<i>Days traveled per year</i>	224	230	226	212	213	224	213	225	213	226	224
<i>Speed of each mode (km/h)</i>	-	-	-	-	-	-	-	-	-	-	-
- <i>BSS (average)</i>	9.60	10	12	12	13.50	8.80	9.90	12	11	12	13.40
<i>BSS (LCI)^a</i>	13.50	13.50	13.50	13.50	13.50	13.50	13.50	13.50	13.50	13.50	13.50
<i>BSS (UCI)^b</i>	8.80	8.80	8.80	8.80	8.80	8.80	8.80	8.80	8.80	8.80	8.80
- <i>Car (average)</i>	21.80	20	26	26	15	25.40	15	26	26	26	38
<i>Car (LCI)^a</i>	45	45	45	45	45	45	45	45	45	45	45
<i>Car (UCI)^b</i>	15	15	15	15	15	15	15	15	15	15	15
<i>Basal level of physical activity (METs)</i>	-	-	-	-	-	-	-	-	-	-	-
<i>Q1</i>	2	2	7.50	5	5	2	5	2	5	2	0
<i>Q2</i>	5.97	10	18	17.50	17.50	5.97	17.50	5.97	17.50	5.97	38
<i>Q3</i>	10	32	50.40	25	25	10	25	10	25	10	58.20
<i>Q4</i>	20	0	0	0	0	0	0	20	0	20	0

Continue from table S8.

BSS by city	Barcelona	Brussels	Hamburg	Lille	Lyon	Milan	Paris	Seville	Toulouse	Valencia	Warsaw
All trips per day BSS	38946	4320	6671	7900	30000	17700	110000	11618	13000	30560	21333
<i>Minimum observed car trips substitution (%)</i>	9.60	7	12	4.70	7	4.70	8	4.70	4.70	4.70	4.70
<i>Minimum observed car trips substitution (trips)</i>	3738.8	302.4	800.5	371.3	2100	831.9	8800	546	611	1436.3	1002.7
<i>Maximum observed car trips substitution (12%)^c (trips)</i>	4673.5	518.4	800.5	948	3600	2124	13200	1394.2	1560	3667.2	2560
<i>If the 50% of BSS trips were substituting car trips (trips)</i>	19473	2160	3335.5	3950	15000	8850	55000	5809	6500	15280	10666.5
<i>If the 100% of BSS trips were substituting car trips (trips)</i>	38946	4320	6671	7900	30000	17700	110000	11618	13000	30560	21333
<i>Expected kilometres travel per trip in the scenario (km)</i>	2.1	4.6	2.9	1.6	2.9	2.7	3.3	2.5	3	1.6	4.2

BSS Bike sharing system

^a LCI Low Confidence Interval; ^b UCI Upper Confidence Interval; ^c 12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included.

*(WHO 2016)

Table S9. Input data used in the analysis for E-bikes.

BSS by city	Barcelona	Madrid	Milan
<i>Inhabitants</i>	1604555	3165883	1345851
<i>Mortality rates 16-64 years (deaths /1000 inhab)</i>	2.05	1.63	1.74
<i>Air pollution average annual concentration (ug/m³)*</i>	15	10	30
<i>Traffic fatalities per billion of km traveled</i>	-	-	-
- <i>Bicycle (average)</i>	5.92	6.08	23
<i>Bicycle (LCI)^a</i>	3.42	3.42	3.42
<i>Bicycle (UCI)^b</i>	89.38	89.38	89.38
- <i>Car (average)</i>	3	3	3
<i>Car (LCI)^a</i>	0	0	0
<i>Car (UCI)^b</i>	8.62	8.62	8.62
<i>Average trips per person/day</i>	3.10	3.53	3.53
<i>Days traveled per year</i>	224	225	224
<i>Speed of each mode (km/h)</i>	-	-	-
- <i>BSS (average)</i>	9.60	12	8.80
<i>BSS (LCI)^a</i>	13.50	13.50	13.50
<i>BSS (UCI)^b</i>	8.80	8.80	8.80
- <i>Car (average)</i>	21.80	23.20	25.40
<i>Car (LCI)^a</i>	45	45	45
<i>Car (UCI)^b</i>	15	15	15

Continue from table S9.

BBS by city	Barcelona	Madrid	Milan
<i>Basal level of physical activity (METs)</i>	-	-	-
<i>Q1</i>	2	2	2
<i>Q2</i>	5.97	5.97	5.97
<i>Q3</i>	10	10	10
<i>Q4</i>	20	20	0
<i>All trips per day BSS</i>	277.29	6935	2300
<i>Minimum observed car trips substitution (%)</i>	9.60	6.40	4.70
<i>Minimum observed car trips substitution (trips)</i>	26.60	443.84	108.10
<i>Maximum observed car trips substitution (12%)^c (trips)</i>	33.28	832.20	276
<i>If the 50% of BSS trips were substituting car trips (trips)</i>	138.65	3467.50	1150
<i>If the 100% of BSS trips were substituting car trips (trips)</i>	277.29	6935	2300
<i>Expected kilometres travel per trip in the scenario (km)</i>	2.07	4.00	2.68

BSS: Bike sharing system

^a LCI Low Confidence Interval

^b UCI Upper Confidence Interval

^c 12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included.

*(WHO 2016)

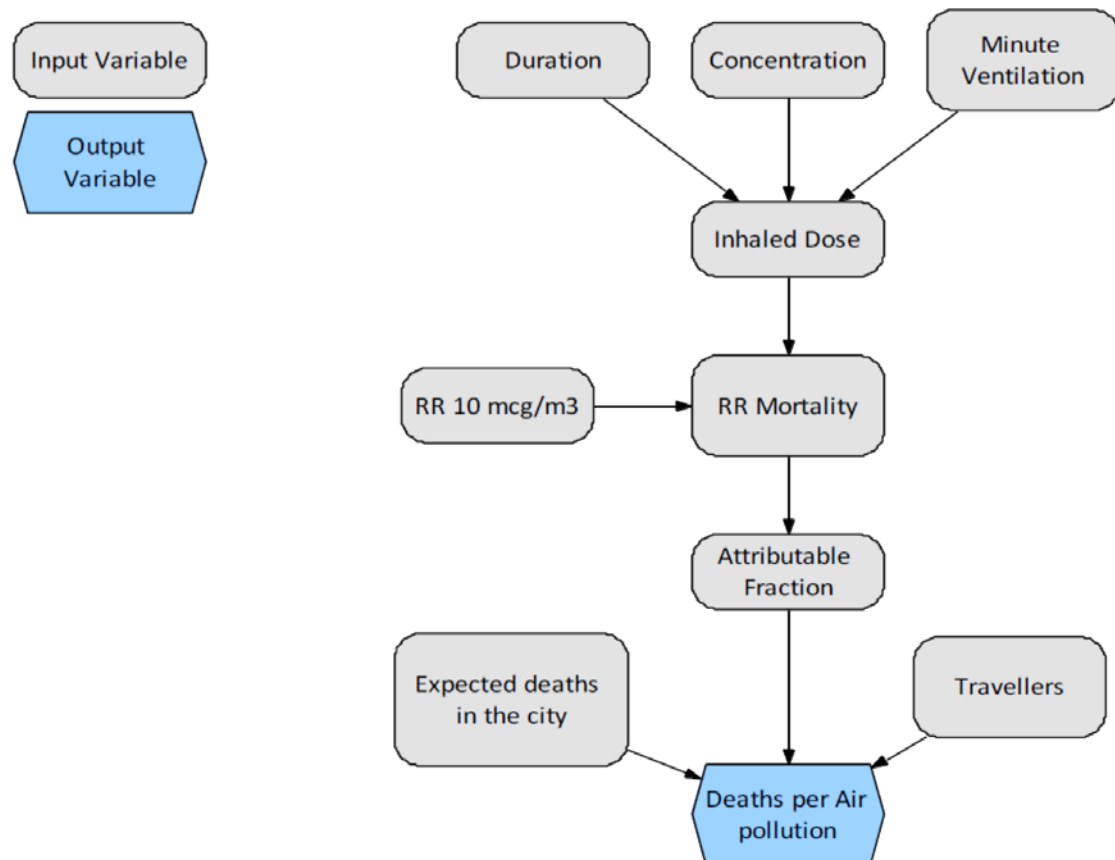
Table S10. Value of statistical life (VSL) by country.

Country with BSS	VSL (Euros)
Belgium	4 380 597
France	4 005 109
Germany	4 232 396
Italy	3 555 826
Poland	5 878 243
Spain	3 202 968

BSS Bike sharing system

Reference:(OECD 2012)

Figure S1. Air pollution model



RR: Relative Risk of all-cause mortality.
 RR10: average adjusted relative risk of all-caused mortality for a 10µg/m3 change of pollutant.

Figure S2. Traffic fatality model

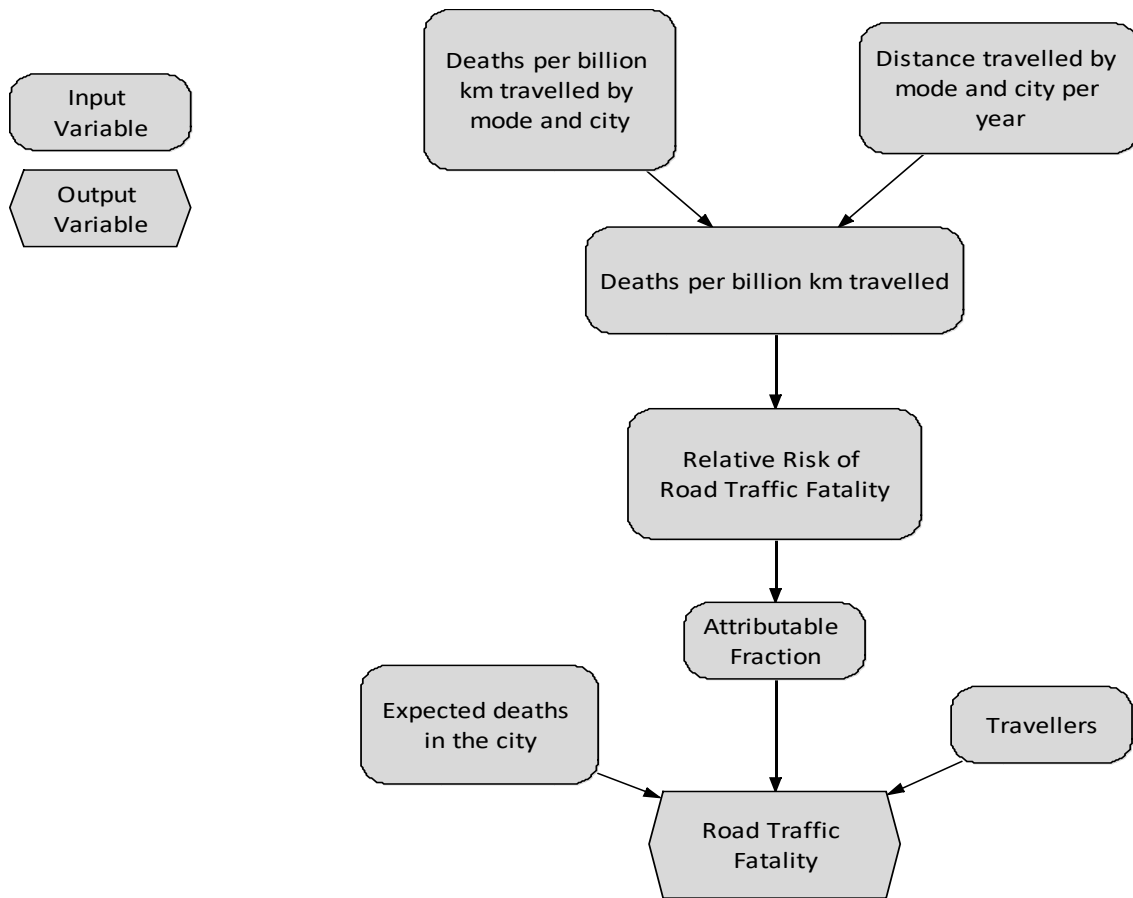
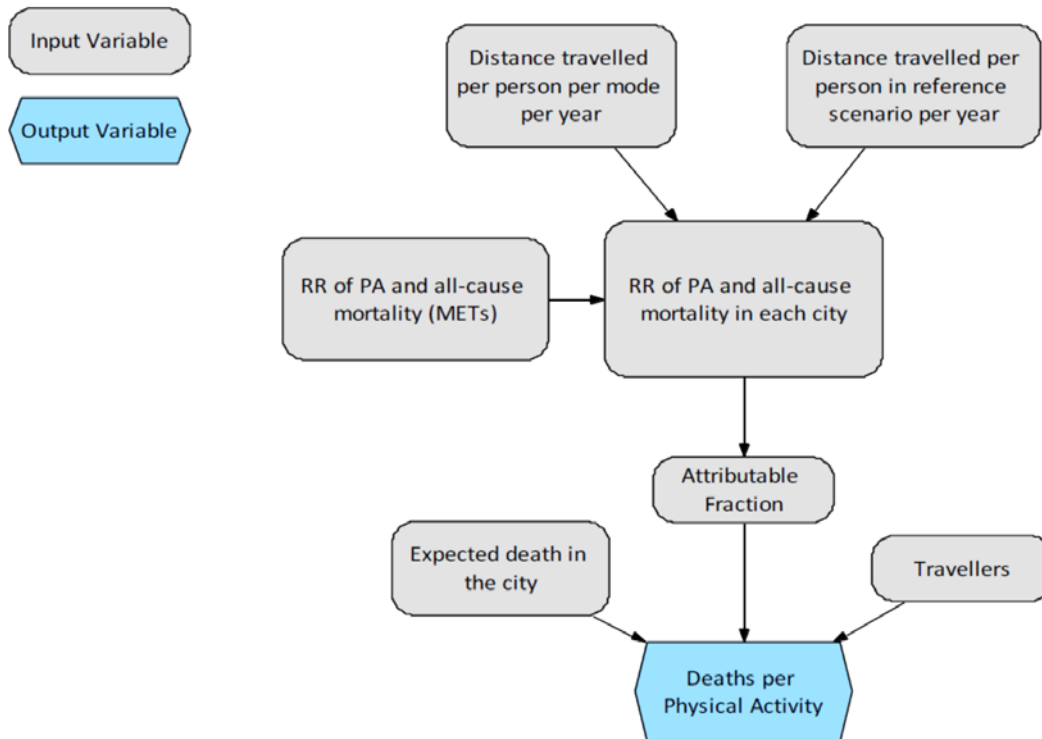


Figure S3. Physical activity model



RR: Relative Risk of all-cause mortality.

Section 2. Results

Table S11. Number of deaths avoided or postponed per year by health determinant in bike and E-bike (standard assistance), minimum observed car trips substitution (scenario 1).

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-0.820	0.011	0.005	-50.682	-0.803 (-1.034, -0.472)
Brussels	-0.082	0.002	0.006	-9.690	-0.073 (-0.102, -0.036)
Hamburg	-0.146	0.002	0.010	-11.970	-0.133 (-0.193, -0.072)
Lille	-0.070	0.001	0.002	-23.033	-0.067 (-0.093, -0.044)
Lyon	-0.507	0.005	0.026	-16.483	-0.476 (-0.685, -0.392)
Madrid	-0.075	0.001	0.003	-17.269	-0.070 (-0.096, -0.008)
Milan	-0.163	0.006	0.012	-9.022	-0.146 (-0.196, -0.069)
Paris	-2.660	0.051	0.073	-21.484	-2.536 (-3.383, -1.476)
Seville	-0.107	0.001	-0.001	-204.404	-0.106 (-0.140, -0.060)
Toulouse	-0.137	0.002	0.008	-14.844	-0.128 (-0.178, -0.075)
Valencia	-0.252	0.002	0.010	-21.529	-0.240 (-0.332, -0.157)
Warsaw	-0.432	0.012	0.020	-13.554	-0.400 (-0.582, -0.250)
Total (95% confidence interval)	-5.450	0.095	0.176	-20.176	-5.178 (-7.011, -3.117)

BSS Bike sharing system

Table S12. Number of deaths avoided or postponed per year by health determinant in bike and E-bike (standard assistance), 12% of BSS trips replaced car trips^a (scenario 2).

^a 12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included.

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-1.025	0.014	0.006	-50.682	-1.005 (-1.292, -0.591)
Brussels	-0.140	0.004	0.011	-9.690	-0.125 (-0.175, -0.062)
Hamburg	-0.146	0.002	0.010	-1.970	-0.133 (-0.193, -0.072)
Lille	-0.180	0.002	0.006	-23.033	-0.172 (-0.239, -0.113)
Lyon	-0.870	0.008	0.044	-16.483	-0.817 (-1.174, -0.671)
Madrid	-0.140	0.002	0.006	-17.269	-0.132 (-0.180, -0.016)
Milan	-0.417	0.015	0.031	-9.022	-0.371 (-0.502, -0.176)
Paris	-3.990	0.076	0.110	-21.484	-3.804 (-5.074, -2.214)
Seville	-0.273	0.004	-0.002	-204.404	-0.272 (-0.358, -0.152)
Toulouse	-0.349	0.004	0.020	-14.844	-0.326 (-0.454, -0.191)
Valencia	-0.643	0.004	0.026	-21.529	-0.613 (-0.848, -0.401)
Warsaw	-1.102	0.031	0.051	-13.554	-1.020 (-1.487, -0.639)
Total (95% confidence interval)	-9.273	0.164	0.319	-19.182	-8.790 (-11.976, -5.304)

BSS Bike sharing system

Table S13. Number of deaths avoided or postponed per year by health determinant in bike and E-bike (standard assistance), 50% of BSS trips come from car trips(scenario 3).

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-4.270	0.057	0.027	-50.682	-4.186 (-5.383, -2.461)
Brussels	-0.582	0.016	0.044	-9.690	-0.522 (-0.731, -0.257)
Hamburg	-0.607	0.007	0.043	-11.970	-0.556 (-0.805, -0.300)
Lille	-0.748	0.006	0.026	-23.033	-0.715 (-0.994, -0.472)
Lyon	-3.623	0.035	0.185	-16.483	-3.403 (-4.890, -2.797)
Madrid	-0.582	0.007	0.027	-17.269	-0.549 (-0.751, -0.066)
Milan	-1.739	0.062	0.131	-9.022	-1.546 (-2.092, -0.734)
Paris	-16.626	0.317	0.457	-21.484	-15.852 (-21.142, -9.225)
Seville	-1.138	0.015	-0.010	-204.404	-1.132 (-1.493, -0.635)
Toulouse	-1.456	0.017	0.081	-14.844	-1.358 (-1.894, -0.794)
Valencia	-2.677	0.017	0.107	-21.529	-2.553 (-3.534, -1.669)
Warsaw	-4.591	0.128	0.210	-13.554	-4.252 (-6.194, -2.663)
Total (95% confidence interval)	-38.639	0.685	1.329	-19.182	-36.624 (-49.903, -22.073)

BSS Bike sharing system

Table S14. Number of deaths per year by health determinant in bike and E-bike (standard assistance), 100% of BSS trips come from car trips(scenario 4).

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-8.541	0.115	0.054	-50.682	-8.372 (-10.766, -4.921)
Brussels	-1.165	0.032	0.089	-9.690	-1.044 (-1.462, -0.515)
Hamburg	-1.214	0.015	0.087	-11.970	-1.112 (-1.610, -0.599)
Lille	-1.496	0.013	0.052	-23.033	-1.431 (-1.988, -0.943)
Lyon	-7.246	0.069	0.370	-16.483	-6.807 (-9.780, -5.593)
Madrid	-1.165	0.014	0.053	-17.269	-1.097 (-1.502, -0.132)
Milan	-3.478	0.124	0.262	-9.022	-3.093 (-4.184, -1.468)
Paris	-33.252	0.633	0.914	-21.484	-31.704 (-42.284, -18.451)
Seville	-2.275	0.031	-0.020	-204.404	-2.264 (-2.986, -1.270)
Toulouse	-2.912	0.033	0.163	-14.844	-2.716 (-3.787, -1.588)
Valencia	-5.354	0.035	0.214	-21.529	-5,106 (-7,067, -3,338)
Warsaw	-9.181	0.257	0.421	-13.554	-8.504 (-12.389, -5.326)
Total (95% confidence interval)	-77.279	1.370	2.658	-19.182	-73.250 (-99.805, -44.144)

BSS Bike sharing system

Table S15. Number of deaths avoided or postponed per year by health determinant in bikes (non-electric bikes), minimum observed car trips substitution (scenario 1).

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-0.814	0.011	0.005	-50.862	-0.798 (-1.027, -0.470)
Brussels	-0.082	0.002	0.006	-9.690	-0.073 (-0.102, -0.036)
Hamburg	-0.146	0.002	0.010	-11.970	-0.133 (-0.193, -0.072)
Lille	-0.070	0.001	0.002	-23.033	-0.067 (-0.093, -0.044)
Lyon	-0.507	0.005	0.026	-16.483	-0.476 (-0.685, -0.392)
Milan	-0.146	0.005	0.010	-9.706	-0.131 (-0.175, -0.065)
Paris	-2.660	0.051	0.073	-21.484	-2.536 (-3.383, -1.476)
Seville	-0.107	0.001	-0.001	-204.404	-0.106 (-0.140, -0.060)
Toulouse	-0.137	0.002	0.008	-14.844	-0.128 (-0.178, -0.075)
Valencia	-0.252	0.002	0.010	-21.529	-0.240 (-0.332, -0.157)
Warsaw	-0.432	0.012	0.020	-13.554	-0.400 (-0.582, -0.250)
BSS Bike sharing system					

Table S16. Number of deaths avoided or postponed per year by health determinant in bikes (non-electric bikes), 12% of BSS trips replaced car trips^a (scenario 2).

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-1.018	0.014	0.006	-50.862	-0.998 (-1.283, -0.588)
Brussels	-0.140	0.004	0.011	-9.690	-0.125 (-0.175, -0.062)
Hamburg	-0.146	0.002	0.010	-11.970	-0.133 (-0.193, -0.072)
Lille	-0.180	0.002	0.006	-23.033	-0.172 (-0.239, -0.113)
Lyon	-0.870	0.008	0.044	-16.483	-0.817 (-1.174, -0.671)
Milan	-0.372	0.013	0.025	-9.706	-0.334 (-0.448, -0.167)
Paris	-3.990	0.076	0.110	-21.484	-3.804 (-5.074, -2.214)
Seville	-0.273	0.004	-0.002	-204.404	-0.272 (-0.358, -0.152)
Toulouse	-0.349	0.004	0.020	-14.844	-0.326 (-0.454, -0.191)
Valencia	-0.643	0.004	0.026	-21.529	-0.613 (-0.848, -0.401)
Warsaw	-1.102	0.031	0.051	-13.554	-1.020 (-1.487, -0.639)
BSS Bike sharing system					

^a 12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included.

Table S17. Number of deaths avoided or postponed per year by health determinant in bikes (non-electric bikes), 50% of BSS trips come from car trips(scenario 3).

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-4.242	0.057	0.026	-50.862	-4.158 (-5.347, -2.449)
Brussels	-0.582	0.016	0.044	-9.690	-0.522 (-0.731, -0.257)
Hamburg	-0.607	0.007	0.043	-11.970	-0.556 (-0.805, -0.300)
Lille	-0.748	0.006	0.026	-23.033	-0.715 (-0.994, -0.472)
Lyon	-3.623	0.035	0.185	-16.483	-3.403 (-4.890, -2.797)
Milan	-1.551	0.056	0.104	-9.706	-1.391 (-1.867, -0.695)
Paris	-16.626	0.317	0.457	-21.484	-15.852 (-21.142, -9.225)
Seville	-1.138	0.015	-0.010	-204.404	-1.132 (-1.493, -0.635)
Toulouse	-1.456	0.017	0.081	-14.844	-1.358 (-1.894, -0.794)
Valencia	-2.677	0.017	0.107	-21.529	-2.553 (-3.534, -1.669)
Warsaw	-4.591	0.128	0.210	-13.554	-4.252 (-6.194, -2.663)

BSS Bike sharing system

Table S18. Number of deaths avoided or postponed per year by health determinant in bikes (non-electric bikes), 100% of BSS trips come from car trips(scenario 4).

BSS by city	Physical Activity <i>deaths /year</i>	Air Pollution <i>deaths /year</i>	Road Traffic Fatality <i>deaths /year</i>	Benefit/risk ratio	Total (95% confidence interval)
Barcelona	-8.484	0.114	0.053	-50.862	-8.317 (-10.694, -4.897)
Brussels	-1.165	0.032	0.089	-9.690	-1.044 (-1.462, -0.515)
Hamburg	-1.214	0.015	0.087	-11.970	-1.112 (-1.610, -0.599)
Lille	-1.496	0.013	0.052	-23.033	-1.431 (-1.988, -0.943)
Lyon	-7.246	0.069	0.370	-16.483	-6.807 (-9.780, -5.593)
Milan	-3.102	0.112	0.207	-9.706	-2.783 (-3.734, -1.390)
Paris	-33.252	0.633	0.914	-21.484	-31.704 (-42.284, -18.451)
Seville	-2.275	0.031	-0.020	-204.404	-2.264 (-2.986, -1.270)
Toulouse	-2.912	0.033	0.163	-14.844	-2.716 (-3.787, -1.588)
Valencia	-5.354	0.035	0.214	-21.529	-5.106 (-7.067, -3.338)
Warsaw	-9.181	0.257	0.421	-13.554	-8.504 (-12.389, -5.326)
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Table S19. Number of deaths avoided or postponed per year by health determinant in E-bikes, minimum observed car trips substitution (scenario 1).

	Barcelona		Madrid		Milan	
	Standard Assistance	High Assistance	Standard Assistance	High Assistance	Standard Assistance	High Assistance
Physical Activity <i>deaths /year</i>	-0.005	-0.005	-0.075	-0.067	-0.018	-0.017
Air Pollution <i>deaths /year</i>	0.0001	0.0001	0.001	0.001	0.001	0.0005
Road Traffic Fatality <i>deaths/year</i>	0.0001	0.0001	0.003	0.003	0.003	0.003
Benefit/risk ratio	-33.180	-32.966	-17.269	-16.655	-5.702	-5.460
Total (95% confidence interval)	-0.005 (-0.007, -0.002)	-0.005 (-0.007, -0.002)	-0.070 (-0.096, -0.008)	-0.063 (-0.087, -0.003)	-0.015 (-0.021, -0.004)	-0.014 (-0.020, -0.003)

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Table S20. Number of deaths avoided or postponed per year by health determinant in E-bikes, 12% of BSS trips replaced car trips^a (scenario 2).

	Barcelona		Madrid		Milan	
	Standard Assistance	High Assistance	Standard Assistance	High Assistance	Standard Assistance	High Assistance
Physical Activity <i>deaths /year</i>	-0.007	-0.007	-0.140	-0.127	-0.045	-0.042
Air Pollution <i>deaths /year</i>	0.0001	0.0001	0.002	0.001	0.001	0.001
Road Traffic Fatality <i>deaths/year</i>	0.0001	0.0001	0.006	0.006	0.006	0.006
Benefit/risk ratio	-33.180	-32.966	-17.269	-16.655	-5.702	-5.460
Total (95% confidence interval)	-0.007 (-0.009, -0.003)	-0.006 (-0.008, -0.003)	-0.132 (-0.180, -0.016)	-0.119 (-0.163, -0.006)	-0.037 (-0.054, -0.009)	-0.035 (-0.051, -0.008)

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^a 12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included.

Table S21. Number of deaths avoided or postponed per year by health determinant in E-bikes, 50% of BSS trips come from car trips(scenario 3).

	Barcelona		Madrid		Milan	
	Standard Assistance	High Assistance	Standard Assistance	High Assistance	Standard Assistance	High Assistance
Physical Activity <i>deaths /year</i>	-0.029	-0.027	-0.582	-0.527	-0.188	-0.177
Air Pollution <i>deaths /year</i>	0.0003	0.0003	0.007	0.005	0.006	0.005
Road Traffic Fatality <i>deaths/year</i>	0.001	0.001	0.027	0.027	0.027	0.027
Benefit/risk ratio	-33.180	-32.966	-17.269	-16.655	-5.702	-5.460
Total (95% confidence interval)	-0.028 (-0.036, -0.012)	-0.026 (-0.034, -0.011)	-0.549 (-0.751, -0.066)	-0.495 (-0.678, -0.024)	-0.155 (-0.225, -0.039)	-0.144 (-0.212, -0.032)

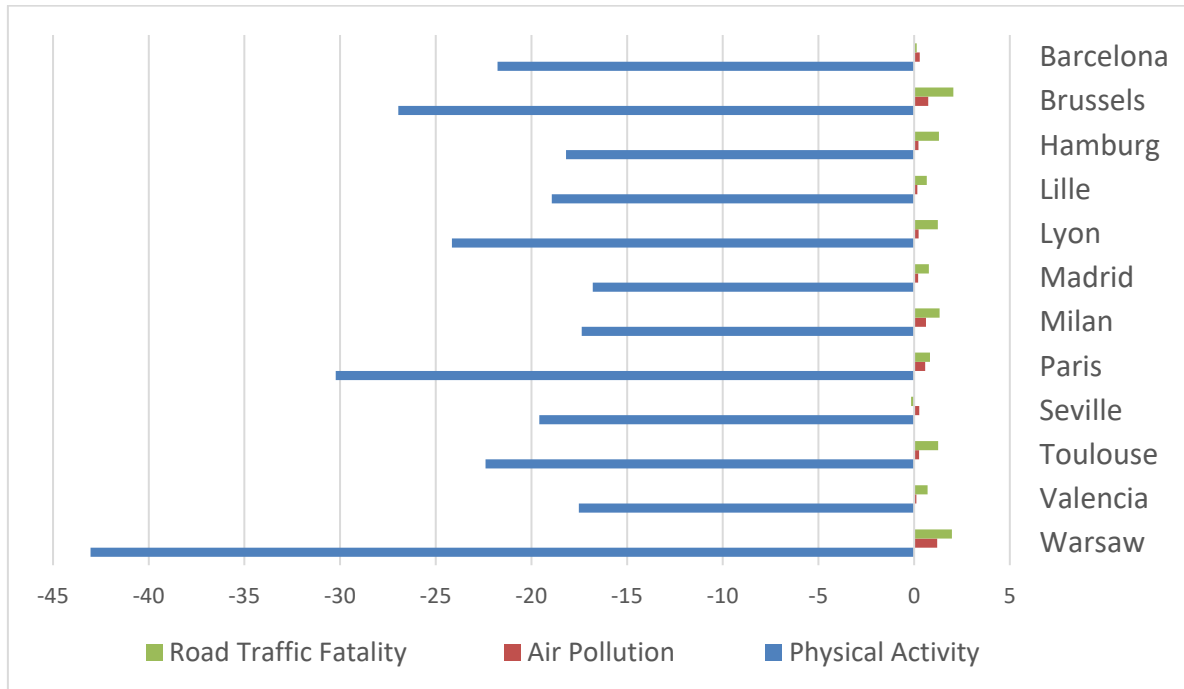
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Table S22. Number of deaths avoided or postponed per year by health determinant in E-bikes, 100% of BSS trips come from car trips(scenario 4).

	Barcelona		Madrid		Milan	
	Standard Assistance	High Assistance	Standard Assistance	High Assistance	Standard Assistance	High Assistance
Physical Activity <i>deaths /year</i>	-0.057	-0.054	-1.165	-1.054	-0.376	-0.353
Air Pollution <i>deaths /year</i>	0.001	0.001	0.014	0.010	0.012	0.011
Road Traffic Fatality <i>deaths/year</i>	0.001	0.001	0.053	0.053	0.054	0.054
Benefit/risk ratio	-33.180	-32.966	-17.269	-16.655	-5.702	-5.460
Total (95% confidence interval)	-0.055 (-0.072, -0.024)	-0.053 (-0.069, -0.022)	-1.097 (-1.502, -0.132)	-0.991 (-1.356, -0.047)	-0.310 (-0.450, -0.078)	-0.288 (-0.425, -0.064)

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Figure S4. Number of annual deaths prevented per year per 100 000 trips, by health determinant, if 100% bicycle trips will replace car trips (scenario 4).



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