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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 > 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 and 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 > 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 23,600 bikes and 1800 stations; other BSS have also reached a considerable large size as London (12,000 bikes), Barcelona (6000), Lyon (4000) or Valencia, Seville, Milan or Brussels with > 2000 bikes. In some

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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 90,000 and 70,000 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 > 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 < 2.5 μm ($PM_{2.5}$)) due to car trips substitution for BSS trips (Fig. 1). The analysis was focused only on BSS with > 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 > 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.

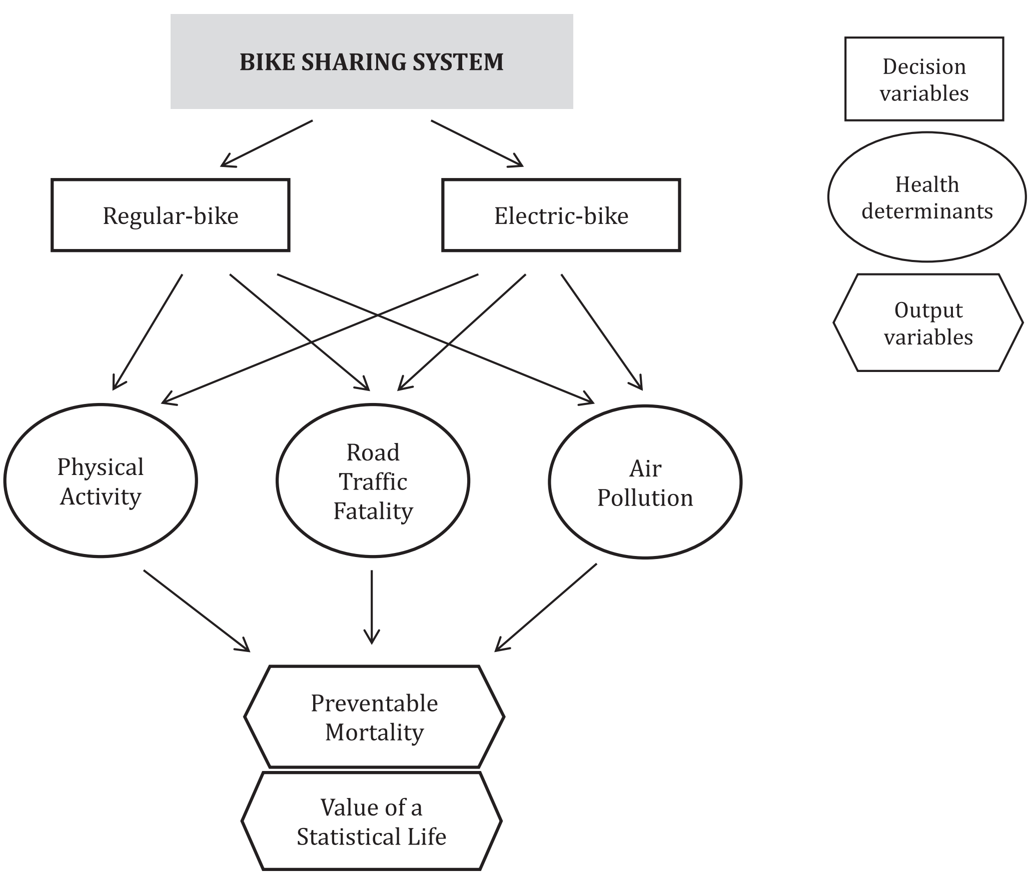

Fig. 1. Conceptual framework of bike sharing systems and health.

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	6000	300	38,946	6,2	2007	Clear Channel
Brussels	1,187,890	Villo	Bike	5000	–	4320	0,9	2009	JCDecaux-Cyclocity
Hamburg	1,787,408	StadtRAD Hamburg	Bike	2450	–	6671	2,7	2009	Deutsche Bahn *"Call a Bike"*
Lille	233,897	V'Lille	Bike	2200	–	7900	3,6	2011	Kéolis
Lyon	506,615	Vélo'v	Bike	4000	–	30,000	7,5	2005	JCDecaux - Cyclocity
Madrid	3,165,883	BiciMAD	E-bike	–	2028	6935	3,4	2014	Bonopark S.L.
Milan	1,345,851	BikeMi	Bike & E-bike	3650	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	2500	–	11,618	4,6	2007	JC Decaux-Cyclocity
Toulouse	466,297	Vélô	Bike	2600	–	13,000	5,0	2007	JC Decaux-Cyclocity
Valencia	787,266	Valenbisi	Bike	2700	–	30,560	11,3	2010	JC Decaux-Cyclocity
Warsaw	1,748,900	Veturilo	Bike	4925	–	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.

Observed substitution			What if…				
BSS by city	Scenario 1		Scenario 2	Scenario 3	Scenario 4		
	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	Increase 10,000 BSS trips per day	Increase 1000 cyclists per day
	Deaths/year (95% CI)	Deaths/year	Deaths/year (95% CI)	Deaths/year (95% CI)	Deaths/year (95% CI)	Deaths/year (95% CI)	Deaths/year (95% CI)
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 (−5.8.07, −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; [a]12% 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.

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 and Kunzli, 2009; World Health Organization, 2008) (Fig. 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 < 2.5 μm ($PM_{2.5}$), 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 $PM_{2.5}$ 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 $PM_{2.5}$ 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., 2011, 2012, 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), $PM_{2.5}$ concentration in the mode of transport and trip duration (Rojas-Rueda et al., 2013, 2011, 2016). The DRF for $PM_{2.5}$ and all-cause mortality from a meta-analysis was used (RR = 1.06 (1.04, 1.08)) for each increment of 10 μg/m^3 of $PM_{2.5}$) (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 Cooperation 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 23,600 in Paris. The BSS trips per day range from 4320 in Brussels to 11,000 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 (Fig. 2).

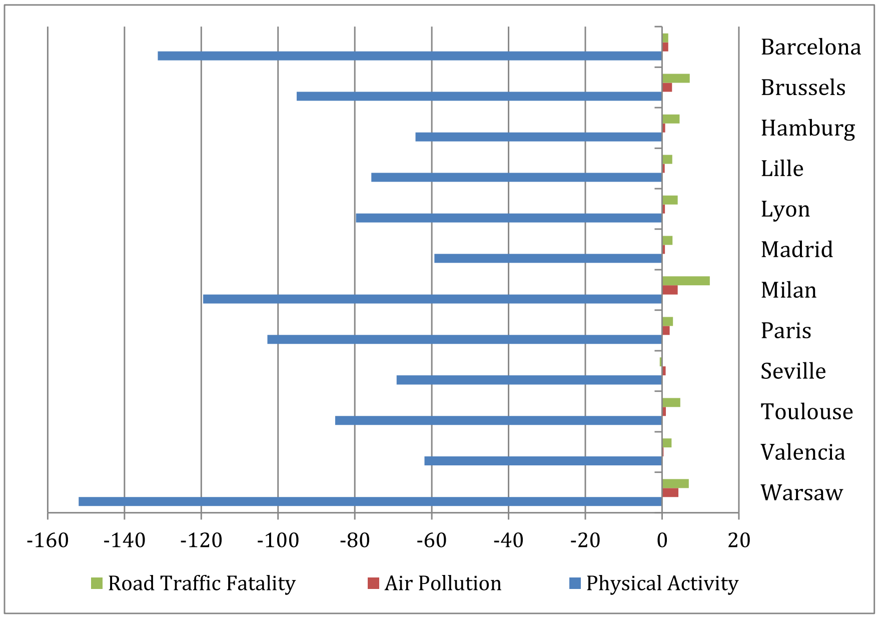

Fig. 2. Number of annual deaths prevented per year per 100,000 cyclists, by health determinant, if 100% of BSS trips come from car trips (Scenario 4).

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 < 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 < 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 < 0.60 annual deaths avoided in each city.

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

	Observed substitution		What if…	
BSS by city	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.
[a] 12% is the maximum reported car trip replacement by BSS trips between the 12 BSS included.

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 < 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 > 18 million Euros. In all the cities and scenarios assessed the health benefits overweighed 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 BBS 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 > 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 and 5000 bikes) and the lowest number of daily trips (between 4320 and 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, where 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. NO_2 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 (Fig. 2). The cities that had the worst levels of air pollution ($PM_{2.5}$) were Milan (30 $\mu g/m^3$) and Warsaw (26 $\mu g/m^3$), but none of the cities assessed had levels under the World Health Organization recommendations (< 10 $\mu g/m^3$) (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 Fig. 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 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 Mobasheri, 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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DR-R study concept. DR-R and IO designed, collected, analyzed and interpreted the data for this study, and they wrote the manuscript. IO, DR-R, and MJN edited and approved the final version for submission.

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Competing interests

All authors have completed the ICMJE uniform disclosure form at www.icmje.org/coi_disclosure.pdf (available on request from the corresponding author) and declare: no support from any organization for the submitted work; no financial relationships with any organizations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval

Not required.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.04.014.

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