RESEARCH

Health effects of the London bicycle sharing system: health impact modelling study

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Abstract

Objective To model the impacts of the bicycle sharing system in London on the health of its users.

Design Health impact modelling and evaluation, using a stochastic simulation model.

Setting Central and inner London, England.

Data sources Total population operational registration and usage data for the London cycle hire scheme (collected April 2011-March 2012), surveys of cycle hire users (collected 2011), and London data on travel, physical activity, road traffic collisions, and particulate air pollution (PM2.5, (collected 2005-12).

Participants 578 607 users of the London cycle hire scheme, aged 14 years and over, with an estimated 78% of travel time accounted for by users younger than 45 years.

Main outcome measures Change in lifelong disability adjusted life years (DALYs) based on one year impacts on incidence of disease and injury, modelled through medium term changes in physical activity, road traffic injuries, and exposure to air pollution.

Results Over the year examined the users made 7.4 million cycle hire trips (estimated 71% of cycling time by men). These trips would mostly otherwise have been made on foot (31%) or by public transport (47%). To date there has been a trend towards fewer fatalities and injuries than expected on cycle hire bicycles. Using these observed injury rates, the population benefits from the cycle hire scheme substantially outweighed harms (net change −72 DALYs (95% credible interval −110 to −43) among men using cycle hire per accounting year; −15 (−42 to −6) among women; note that negative DALYs represent a health benefit). When we modelled cycle hire injury rates as being equal to background rates for all cycling in central London, these benefits were smaller and there was

no evidence of a benefit among women (change −49 DALYs (−88 to −17) among men; −1 DALY (−27 to 12) among women). This sex difference largely reflected higher road collision fatality rates for female cyclists. At older ages the modelled benefits of cycling were much larger than the harms. Using background injury rates in the youngest age group (15 to 29 years), the medium term benefits and harms were both comparatively small and potentially negative.

Conclusion London's bicycle sharing system has positive health impacts overall, but these benefits are clearer for men than for women and for older users than for younger users. The potential benefits of cycling may not currently apply to all groups in all settings.

Introduction

Physical inactivity is a major cause of morbidity and mortality,[1] and the creation of opportunities for safe, active mobility has been identified as one central feature of a "healthy city."[2] Promoting a shift away from motorised vehicle travel towards walking and cycling would also be expected to yield additional health, economic, and environmental benefits, including reducing traffic congestion, noise, and the emission of greenhouse gases.[3-5] One way in which cities can seek to realise these benefits is by implementing bicycle sharing systems to facilitate short term bicycle rental in urban areas. Typically, users of these schemes can borrow a bicycle from any one of several self service stations and drop it off at any other station, making cycling into a form of public transport. Such schemes are increasingly popular around the world, having grown from five schemes in Europe in 2000 to 636 schemes (with an estimated 600 000 bicycles) in 49 countries in 2013.[6]

Although the proliferation of bicycle sharing systems has attracted research attention, most studies have focused on the uptake of the scheme, the movement of bicycles around the city, or the characteristics and behaviour of users.[7-11] To our knowledge, only one study has modelled health impacts, estimating the effects of the Barcelona bicycle sharing system on all cause mortality.[12] This study found a large benefit to harm ratio in favour of the scheme but had limited data on usage of the scheme or on the likely personal characteristics of scheme users. The Barcelona evaluation also only assessed the health impacts on mortality and did not consider the effects on morbidity.

With access to complete registration and usage data, we modelled the impact of the bicycle sharing system in London on the health of its users. Specifically, we sought to model both the mortality and the morbidity impacts of the scheme on male and female users of different ages, by estimating changes in their physical activity, road traffic injury rates, and exposure to air pollution.

Methods

The London cycle hire scheme

The London cycle hire scheme is the local name for the bicycle sharing system that was launched in London in July 2010. The scheme operates 24 hours a day, 365 days a year, and initially comprised 5000 bicycles located across 315 docking stations in central London. Following an eastern extension in March 2012, the scheme grew to comprise 8000 bicycles at 571 docking stations. Users can either register online for an access key (registered users) or pay by credit or debit card at docking stations (casual users). See appendix 1 for maps and further details.

Health impact modelling

We modelled the health impacts of the London cycle hire scheme by comparing the effects of the scheme against a counterfactual scenario in which it did not exist. Health impacts were modelled through changes in physical activity and exposure to air pollution (using a comparative risk assessment approach) and in road traffic injuries (using a risk and travel time based approach). Our primary outcome metric was lifelong change in non-discounted, non-age weighted disability adjusted life years (DALYs), calculated as the sum of years of life lost owing to premature mortality (YLL) and years of healthy life lost due to disability (YLD). We calculated impacts in terms of the effect across the users' life course from one year changes in incidence of disease and injury. For example, if the cycle hire scheme averted one fatality per year in a given age group, the gain in DALYs assigned to that year would include all the future years of healthy life that would be expected for someone in that age group. All changes in exposure were assumed only to affect people in their current 10 to 15 year age band—that is, we did not include lags to capture possible longer term effects.

Our modelling used a revised version of the integrated transport and health impact modelling tool,[3 4] implemented in Analytica Lumina 4.4 (see appendix 2 for details of the model's specification). This included stochastic uncertainty analyses around key parameter estimates. It also included deterministic "what if" sensitivity analyses, examining the sensitivity of our findings to key aspects of the London context (for example, background air pollution and injury rates) and so exploring the generalisability of our findings to other settings. Table 1⇓ summarises the key modelling data sources and sensitivity analyses, with details provided in appendix 3.

Usage of the London cycle hire scheme: operational data supplemented by survey data

Transport for London provided data on operational usage for all cycle hire trips made between 30 July 2010 and 31 March 2012, including trip level data for the final 12 months. This trip level data included a unique ID for each user and the start and end time and location of each trip. It also included the sex and area of residence of registered users; no personal data were available for casual users. We estimated the age structure of cycle hire users and the modal shift attributable to cycle hire using the best data available—namely, two surveys conducted during July 2011 by Transport for London (2652 registered users in an online survey, 1034 casual users in an intercept survey). Both surveys recorded age and sex, and the online survey also asked respondents to report the duration of their most recent cycle hire trip and what alternative mode they would typically have used for that trip before cycle hire was introduced. Although there is no direct way to establish the representativeness of these samples, these survey data did generate accurate estimates of those values that could be cross checked against the operational data—for example, in the surveys, 76.6% of registered users were male (2031/2652) compared with 75.9% in the operational data (69 893/92 100).

Physical activity

We modelled distributions of physical activity using marginal metabolic equivalent of tasks (MET) values (hours per year), for four different domains, each calculated separately by sex and age group. Three distributions were assumed to change: cycling on cycle hire bicycles increased by the amount observed in the operational data, whereas own bicycle cycling and walking decreased by the estimated duration displaced by cycle hire trips. We assumed the other domain, incorporating activity from work, sport, and house or garden tasks, to remain unchanged. To allow for the possibility that cycle hire may appeal more to those who are already somewhat active in other areas, we assumed the baseline activity levels of cycle hire users to lie between those of existing cyclists and those of the general population (see appendix 3).

We took the median marginal MET values for each activity domain from a physical activity compendium,[13] with values of 1.5 and under not counted towards total physical activity. Marginal MET values refer to the intensity of an activity minus 1 (the intensity of being at rest). The short walks involved in getting to a bus or underground stop in central London were assumed to be balanced out by the short walks involved in getting to a cycle hire docking station, and therefore were not included in the MET values lost from former trips on public transport. To generate a distribution of total physical activity we stochastically combined the distributions of METs from different domains. We modelled health impacts by comparing the median MET exposures for each 10th of this total distribution, with and without the changes attributed to the cycle hire scheme.

A systematic overview[14] provided relative risks for associations between physical activity and breast cancer, ischaemic heart disease, stroke, colon cancer, dementia, depression, and diabetes (see table 14 in appendix 3). Given evidence of a non-linear relation between physical activity and health,[15 16] we assumed changes in risk of disease to be log linearly associated with a power transformation of the physical activity exposure (stochastically modelled with mode power 0.5, range 0.25-1).

As a sensitivity analysis, we modelled the impact of physical activity on all cause mortality directly rather than through

changes in individual diseases. We did this twice—firstly, using the estimated exposure response function from a recent systematic review[16] and, secondly, taking relative risks for different levels of physical activity directly from a subsequent cohort study of 400 000 adults.[17] We applied stochastic scaling factors to represent the observation that relative risk reductions are smaller at younger ages,[17] probably as a result of the different composition of causes of deaths.

PM2.5 air pollution

Among urban air pollutants, by far the largest health impact in Europe comes from PM2.5 (particles with a diameter of ≤2.5 μm).[33] We estimated changes in the PM2.5 exposure rate associated with using the cycle hire scheme as: exposure rate=average PM2.5 concentration along route×ventilation rate×road position scaling factor×pollution composition factor.

To calculate this, we modelled the most likely route for each observed cycle hire trip (fig 1⇓), and for four counterfactual modes (own bicycle; walking; car, van, motorcycle, or taxi; and bus). We modelled these routes using Routino (www.routino. org) software algorithms, calibrated to each mode (for example, cyclists will usually prefer cycle lanes and quieter roads, buses will avoid minor roads). We then estimated the exposure to PM2.5 along each route by applying published estimates of average 24 hour PM2.5 concentrations in 2008 in a 20 m² grid across central London.[31] For the London underground, we took data from academic papers[18] and assumed they did not vary by route. We multiplied these concentrations by three sets of scaling factors to represent the facts that cyclists and pedestrians tend to inhale higher concentrations of pollutants because of their greater ventilation rates, whereas motorised road users tend to experience slightly higher pollution concentrations because of their proximity in the road to the emissions from other motor vehicles,[19] and that the composition of PM2.5 pollution in the underground may render it less harmful to health than surface level PM2.5.

To estimate a change in daily total exposure we multiplied the time spent travelling in each mode by that mode's exposure rate, assuming that the exposure for the rest of the day was 14.91 μg m⁻³ (the 2008 average for inner London). To estimate the resulting impacts on cardiovascular disease, respiratory disease, and lung cancer, we used values recommended by the World Health Organization.[22]

Road traffic and other transport injuries

We captured health impacts from transport injuries in two ways. Firstly, we used observed injury rates, based on recorded injuries involving a cycle hire bicycle in the first 21 months of cycle hire. Numerator data were provided by Transport for London, which had collated any routinely collected police injury report[32] that noted a cycle hire bicycle (London police were asked to note these) plus a few further incidents that were reported to the London cycle hire customer service number and subsequently confirmed by the police. For the denominators we used the total travel time during cycle hire use recorded in the operational usage data.

Our second approach used modelled injury rates, assuming the rates of cycle hire injury were the same as for cycling in general in the cycle hire zone between 2005 and 2011. For the numerators we used routinely collected police data[32] to identify the number of men and women aged 16-60 who were killed, seriously injured, or slightly injured in road collisions in the cycle hire zone. To these we added additional non-intentional fatalities and major injuries on London's public transport.[23] For

the denominators we estimated total travel time by each mode for men and women aged 16-60 travelling within the cycle hire zone.[24 27] We then used scaling factors to estimate risks for different age groups and to capture, for example, the observation that the risks of injuries from cycling increase with age.[34] To have samples large enough to produce reliable estimates at the oldest age groups (see tables 21-22 in appendix 3), we created these scaling factors using data from the Netherlands for 2002-09.[35] The shape of the age associations was similar to those reported for London[36] and the United Kingdom.[34]

In both approaches we applied London specific scaling factors to account for under-reporting of injuries to the police.[25] We then estimated the number of deaths, serious and slight injuries that would be expected among cycle hire users in the past year, and also the number that would be expected to be averted by reductions in times spent in other modes. We converted these to estimates of DALYs and premature deaths.

Results

Levels of London cycle hire use, characteristics of cycle hire users, and modal shift through cycle hire

Between April 2011 and March 2012, 578 607 unique cycle hire users made a total of 7.4 million cycle hire trips and thereby generated 2.1 million hours of use (table 2⇓; also see appendix 1 for trip rates across the first 20 months). Put into context, this equates to 12.1% of the estimated 61.2 million cycle trips made by adults each year that started or ended in the cycle hire zone, and 10.1% of the estimated 20.8 million hours of cycling duration.[24 27]

Table 3⇓ presents the estimated proportions of cycle hire travel time accounted for by men and women of different ages among these 578 607 unique users. The majority of cycle time was accounted for by men (71.0%) and by those aged between 15 and 44 (78.1%), with only an estimated 2.5% of travel time being accounted for by those aged more than 60 (see tables 2-5 in appendix 3). Other sociodemographic data were not available on the cycle hire population as a whole, but registered users in the survey were disproportionately likely to be in full time or part time work (93.0% (2424/2607) v 62.4% among adults in London as a whole[37]), to be from relatively affluent households (for example, 64.6% (1423/2204) with an annual household income over £50 000 v 20.7% in London as a whole[27]), and to identify themselves as White British (69.3% (1754/2531) v 44.9% in London as a whole[37]).

As shown in table 4⇓, survey data indicated that most cycle hire trips would otherwise have been made by public transport (midpoint estimate 47% based on modelled analysis combining casual and registered users) or active travel (31% walking, 7% cycling), with a much smaller proportion otherwise made by car, van, taxi, or motorcycle (6%) or not made at all (midpoint estimate 9%; modelled with uncertainty, see table 1 in appendix 3). We estimated that, on average, using the cycle hire reduced journey times by around 20% (see appendix 3). Table 4 also shows the physical activity, air pollution, and injury parameters estimated and modelled as being associated with each of these alternative modes.

Physical activity

Most cycle hire users used the scheme infrequently (table 3). Our model estimated that mean physical activity increased by an average of 0.06 MET hours per week per person. Although this is small on average at the individual level, it led to notable

modelled gains in health at population level. The pattern of the benefits differed between men and women owing to the different disease burdens and, to a lesser extent, the different age structure of the populations. Among men, almost half the benefit in terms of DALYs was from reductions in ischaemic heart disease, whereas among women the largest benefit was from reductions in depression (table 5⇓).

Air pollution

Modelled average route concentrations for PM2.5 were somewhat lower for walking and bicycle trips than for road based motorised trips, but this was more than counterbalanced by higher ventilation rates (table 4). All routes by road transport were associated with much lower exposure to PM2.5 than those reported on the London underground. In aggregate across all trips, the benefit from the averted exposure to PM2.5 in the underground approximately balanced the harms from increased inhalation of pollutants as a result of the higher ventilation rates associated with cycling. Therefore, the impact of cycle hire use on average daily exposure was small. Removing the air pollution component of the model had only a small effect on the overall health impacts—for example, from a change of −83.2 DALYs for men from physical activity alone to −82.8 DALYs from physical activity and air pollution (see table 26 in appendix 4).

Road traffic injuries

Between 2005 and 2011, injury rates in the cycle hire zone were generally highest by a substantial margin for motorcycling, followed by cycling, walking, car or van, and bus, and finally train, underground, and taxi (table 4). One notable observation was that the fatality rate among female cyclists was high relative to both other modes of travel and relative to men. This reflected a higher number of cycling fatalities in women involving heavy goods vehicles (weighing >3.5 tonnes). Twice as many women as men were killed in collisions involving heavy goods vehicles (15 women *v* 7 men), despite women only accounting for an estimated 30% of total cycling time and having half as many fatalities not involving heavy goods vehicles (5 women *v* 10 men, P=0.04 for a sex difference in probability that a cycling fatality involved a heavy goods vehicle).

In all cases the observed injury rates while using the cycle hire scheme were lower than those estimated for cycling in general, including no reported fatalities as of end April 2012 (table 4). This trend was only significant for slight injuries (P<0.001 for both men and women) and perhaps serious injuries for men (P=0.08). The other comparisons were underpowered because of the comparatively small total duration of cycle hire travel, and they were non-significant (all P>0.8). Including the one cycle hire fatality that had occurred as of end November 2013 did not alter this picture of a non-significant trend towards lower cycle hire fatality rates than would be expected given background fatality rates (see appendix 3).

Combined results

Overall, we found reductions in the disease burden of cycle hire users when using either observed or background cycling injury rates (table 5), although the size of the effect differed. Using observed injuries, the total benefit for the whole population was a change of −88 DALYs per year (95% credible interval −148 to −51: note that negative values for DALYs represent a health benefit). Using background cycling injury rates to estimate injury rates during cycle hire, the benefits were smaller (−50 DALYs per year, −111 to −9).

When we stratified the results by sex we found smaller benefits among women. Allowing for higher usage among men, this sex difference was small when using observed cycle hire injury rates but became noticeable when using background injury rates, with no evidence of a benefit among women (change of −1 DALY, −27 to 12). Using background injury rates, we also found considerable variation by age in the harm-benefit trade-off of cycling in the cycle hire zone (fig 2⇓, see also table 28 in appendix 4). This variation was affected by three factors. Firstly, the incidence of disease increases with age and we were only modelling medium term health benefits within 10-15 year age bands. Secondly, our analyses of data from the Netherlands indicated that the fatality risk while cycling increases at older ages (see tables 21 and 22 in appendix 3), probably in the main reflecting greater frailty. Thirdly, owing to lower life expectancy, years of life lost per event decrease with age, so deaths or injuries at older ages translate into fewer DALYs than comparable events at younger ages. These effects operate in different directions: at older ages, rising disease incidence increases the magnitude of the benefits, increasing injury risk increases the magnitude of the harms, and lower life expectancy decreases the magnitude of both benefits and harms. Overall, the rising incidence of disease had a larger effect than the increasing risk of injury in our model, which in turn had a larger effect than the decreasing life expectancy.

As a result, modelled harms and benefits both increased with age but the benefits increased faster. As a consequence of this, from age group 45-59 years onwards the benefits substantially outweighed the harms. In the age group 30-44 years the benefits also marginally outweighed the harms (fig 2). In the youngest age group (15-29 years) our model found that both the harms and the benefits (from changes to incidence of disease and injury within that age range) were much smaller in absolute terms than at older ages. The midpoint estimates from the individual disease model suggested that in this age group the medium term harms (given the relatively high risks in central London) could outweigh the benefits, but with considerable uncertainty: a change of 26 DALYs (95% credible interval −20 to 56) in males and 41 DALYS (−24 to 75) in females. Further uncertainty, relating to model structure, is suggested by our sensitivity analyses, which indicated that this individual disease model may be underestimating the benefits from physical activity. Specifically, when we modelled the health effects of physical activity directly on all cause mortality, we found notably larger benefits in terms of years of life lost owing to premature mortality than were estimated when modelled through individual diseases (table 5).

Stochastic and deterministic uncertainty analyses

In both sexes, the key sources of stochastic uncertainty included the age distribution of the population and the power transformation of the exposure to physical activity (see figures 4-5 in appendix 4). Other substantial contributors were the effect of physical activity on heart disease (particularly in men) and the background cycling fatality rate (particularly in women). The relative risk for the effect of physical activity on depression was also important for women, as were the weighting factors related to serious injuries for men. The other factors examined played a more minor role.

Among our five deterministic "what if" analyses, we found that changing the age structure of the population would have the biggest impact on the results, with an older population of cycle hire users leading to a large increase in the health benefits in both sexes (fig 3⇓). The second most important change would

be to make the injury rate the same as that in the Netherlands, which again would noticeably increase the health benefits observed. Other changes were less important. The net benefits would increase if baseline physical activity among cycle hire users was closer to the England and Wales average and not, as our model assumes, greater than the average for London (an area in which walking is higher than the national average[38]). There would also be a smaller increase in the net benefit among users if all cycle hire trips would otherwise have been made by car. Lastly, there would be little change in the results if the cycle hire scheme were implemented in a more polluted European or North American setting.

Discussion

In this health impact modelling study our estimates suggested benefits from the introduction of a bicycle sharing system (cycle hire) in London, with these benefits reflecting reductions in diseases affected by physical inactivity. These modelled benefits were larger than either observed or modelled changes to injuries, whereas changes in exposure to air pollution were small. The ratio of benefits to harms differed noticeably by age and sex, however, with a more favourable trade-off among older people (who in practice used the cycle hire scheme rarely) and among men (who in practice accounted for most of the cycle hire use). Indeed, when using background injury rates the benefits and harms to women were of a similar size, reflecting the comparatively high background fatal injury rate for female cyclists in central London. Reducing these background rates to the level seen in the Netherlands would substantially improve the harm to benefit trade-off both for female cycle hire users and for young people. The largest improvement to the population impact of the scheme itself would be from increasing the level of cycle hire use among middle aged and older adults.

Strengths and weaknesses of this study

This study enjoyed better usage data than have been available to studies of bicycle sharing systems in other settings,[12 39] including high quality, total population data at the individual and trip level. Our data were more limited, however, for age and modal shift (although better than the previous health modelling study of a bicycle sharing system[12]), and we also lacked user specific information on baseline physical activity or health. Our reliance on police injury records rather than hospital statistics means that we have probably underestimated the risk to pedestrians from falls and so overestimated somewhat the difference in injury rates between cyclists and pedestrians.[34] We may also have overestimated injury risks to cycle hire users for two other reasons. Firstly, we parameterised our model using data from 2005-11, but there is some suggestion that injury risks are decreasing in London as a whole.[36] Secondly, cycle hire has not been operating long enough to allow cycle hire specific injury rates to be estimated with precision. We therefore chose additionally to present models using the apparently higher background cycling injury rates.

As for our modelling approach, strengths include presenting harms and benefits stratified by age group and sex, estimating mode specific exposure to air pollution, and examining the sensitivity of the results to multiple parameters and structural elements. Although our findings are specific to London and do not necessarily apply to bicycle sharing systems elsewhere, our "what if" analyses provide some indication as to the likely effect of some differences in context or usage patterns. These results can help policy makers outside London estimate how the impact of their scheme might compare and can provide an indication

to London policy makers of how benefits might be improved. One limitation is that we only modelled health benefits from short to medium term behaviour change, without time lags. That is, we did not model the possibility that cycling at a particular age increases cycling across the life course or otherwise affects disease incidence at older ages. Reliable data on such long term effects are limited, but their omission from our model may have underestimated the lifetime health benefits to those who start cycling at young ages. Our model was also limited to those outcomes for which there was consistent evidence of effects and effect sizes from systematic reviews of cohort studies. Among potential adverse effects we did not model an effect of cycling on erectile dysfunction,[40] as there is little evidence that rates of this condition are increased for cyclists doing low to moderate amounts of cycling on non-sports bicycles (indeed, modest rates of cycling might be protective owing to the benefits from physical activity).[41 42] A third potential limitation is that we only modelled the impacts of air pollution and injury on cycle hire users and not on the wider population of Londoners. However, it is unlikely that these wider impacts would have been substantial, given that few cycle hire trips would otherwise have been made by car. Finally, our study has been limited to considering the likely health impacts of cycle hire in the short to medium term. A more comprehensive assessment would also need to consider the financial costs, impacts in other sectors (for example, easing congestion or encouraging tourism), and potential indirect or longer term effects not considered here (for example, the possible impact of cycle hire in normalising cycling by encouraging cycling while wearing everyday clothing[43 44]). Of particular relevance to transport economists is the estimated 20% average time saving for trips made using the hire bikes as opposed to the alternative modes used previously.

Meaning of the study and directions for future research

A trend towards lower injury rates on London bicycle sharing system

When the London cycle hire scheme was launched, concern was expressed in the press[45] and in the consultation process[46] that cycle hire users would face higher injury rates. Like one previous Canadian study,[47] our findings are reassuring in finding no evidence that cycling on a bicycle sharing system is more dangerous than own bicycle cycling. Indeed, if anything our results suggest that using cycle hire bicycles may be safer than cycling in general in central London, although to date the comparisons are underpowered. Why this may be true merits further research. Helmets are not provided with the cycle hire bicycles and have been reported in London[43] and elsewhere[10 48] to be used less often by cycle hire users. More plausible explanations could include characteristics of the bicycles (slower and with built-in lights), patterns of cycling (for example, a higher proportion of cycling in parks), or the behaviour of drivers (potentially driving with greater care around cycle hire users[49]).

Role of heavy goods vehicles in comparatively high background fatality rates in central London

When using background cycling injury rates, the ratio of benefits to harms was much less favourable among female cycle hire users than among males. This partly reflected females' younger age distribution and lower disease burden, but mostly reflected a higher background rate of fatal injuries from heavy goods vehicles. These injury figures are taken from a relatively small

area of inner London and should not be regarded as applying to all cycling in London.

It is unclear why, both in this study and in previous research in London using earlier data,[50][51] female cyclists in central London seem to be at greater risk from heavy goods vehicles. Explanations involving the behaviour of female cyclists need to consider the generally lower risks that women face[42] and to avoid an exclusive focus on the individual cyclist's behaviour at the expense of questioning infrastructure or the responsibility of drivers.[44] Finally, attention to women should not detract from recognition that heavy goods vehicles also contribute a substantial proportion of fatalities among men and therefore represent a priority for making cycling safer for all Londoners.[51-53]

Key influences on health impacts of bicycle sharing systems

Although we found health benefits to cycle hire users, the magnitude of these benefits is considerably smaller than those reported in the study modelling the impacts of the Barcelona bicycle sharing system.[12] For example, our three different modelling approaches generated estimates of 3.3 to 10.9 deaths averted per million users per year in London versus 69.2 in Barcelona. Firstly, this reflects methodological differences in how the health benefits of physical activity were modelled, with our disease specific model producing smaller effects for a given age group than the approach used by the Barcelona study[4] which used relative risks for all-cause mortality derived from the health economic assessment tool (HEAT) for cycling and walking model.

Secondly, the result reflects observed differences between the settings, in terms of both age and risk of injury. Both our sensitivity analysis and that of the Barcelona study indicate the importance of the age of users for the size of the benefits. Our data on age suggest a younger population than that assumed for Barcelona. The model parameters in our study drew on better data than were available to the Barcelona study and are also more consistent with the international literature on usage of bicycle sharing systems.[10] In terms of cycling fatality risk, the Barcelona study used a low risk (nearly four times lower than the Netherlands[35] and 18 times lower than Spain as a whole[12]), whereas we used the comparatively high background injury rates in central London (which are notably higher than in the Netherlands).

Age and injury risk work together to produce our comparatively small effect. This estimation of age specific effects contrasts with most health modelling studies of walking and cycling, which typically only present aggregate harms and benefits based on a change across age groups in a population, and which therefore find large net benefits.[3][12][14] One exception considered mortality but not morbidity in a low risk environment for cycling (the Netherlands) and found smaller absolute effects at younger ages but consistent and large harm benefit ratios (compared with car driving) across all age groups modelled.[5] Our findings introduce a note of caution, suggesting that among young people the benefits of cycling do not necessarily outweigh the harms in settings with high injury rates, at least in the medium term. One important question for future, longitudinal research is how far using a bicycle sharing system at a young age increases the probability of cycling on hire bicycles or on personal bicycles at an older age; to the extent that this occurs, we will have underestimated the long term benefits to young cycle hire users who continue cycling in later life.

At present, however, cycle hire users are considerably younger than the London population. Our findings indicate that benefits could be substantially increased both by increasing the share of trips made by older users and by reducing the risks of injury. Although the benefits from increasing the share of trips by older users are larger, it may be more efficacious to reduce the risk of injury first as this is the most commonly given reason for not cycling in London.[54] In the Netherlands, a comprehensive and well maintained system of cycle tracks, physically protected from fast motor traffic, have helped to make cycling widespread at all ages[35] and reduce the risks of injury.[55] Providing similar quality infrastructure in London might help realise the substantial potential health benefits that cycling could offer at population level.[4]

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What is already known on this topic

Cycling is a physically active and environmentally sustainable form of transport that poses low harms to others

Cyclists may, however, face a higher risk of road injury and inhale greater quantities of pollutants than most other road users

Over 600 cities have implemented bicycle sharing systems

What this study adds

The London bicycle sharing system appears to have had a positive overall health effect, but the benefits per capita appear smaller than that estimated for the Barcelona bicycle sharing system owing to differences in data availability, modelling techniques, and risk of injury

The net benefits of cycling in central London are much larger among older adults; in the youngest age groups, medium term harms and benefits are both much smaller, and there is the potential for negative net effects

Realising the population health benefits requires creating safe and inviting environments for cycling across the life course

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Tables

Table 1| Summary of key model inputs, data sources, and uncertainty and "what if" analyses

Input	Sources for model variables	Modelled with variability	Uncertainty analysis	"What if" analysis
Cycle hire:				
Usage	D1	No	No	No
Duration of cycle hire travel time in past year	D1	Yes	No	No
Age structure and sex split of population with % cycle hire travel time	D1, D2, D3	No	Yes, for age	Yes
% trips newly generated by cycle hire	D2	No	Yes	No
Modal shift among trips not newly generated	D1, D2	No	No	Yes
Physical activity model:				
Counterfactual (baseline) active travel, and change resulting from cycle hire	D1, D2, D4, D5	Yes	Yes	Yes
Counterfactual (baseline) other physical activity	D6	Yes	Yes	Yes
MET intensity in different activities	D5, D6, [4 13]	Yes, for cycling	No	No
Health impacts of physical activity, through specific diseases	D7, [14 15]	No	Yes	No
Health impacts of physical activity, directly through all cause mortality	D8, [16 17]	No	Yes	No
Smaller mortality reduction from physical activity at younger ages	17	No	Yes	No
Air pollution model:				
PM2.5 concentration along cycle hire and counterfactual routes	D9, D10, [18]	No	Yes, for underground	Yes
Pollution scaling factors in different modes	13 19-21	Yes, through MET variability	No	No
Health impacts of PM2.5	D7[21 22]	No	Yes	No
Injuries model:				
Observed injury rate for cycle hire	D1, D11	No	No	No
Modelled injury rate for counterfactual modes	D4, D12, [23 24]	No	Yes	Yes
Under-reporting of injuries in routine data	25	No	Yes	No
Health burden of injuries	D7, [26]	No	Yes	No

D=datasets; MET=metabolic equivalents of task; PM2.5=air pollution particles of diameter ≤2.5 μm.

D1=operational registration plus data on cycle hire usage, July 2010-March 2012, provided by Transport for London, including trip level data for final 12 months (1 April 2011 to 31 March 2012).

D2=online survey of 2652 registered users July 2011, provided by Transport for London.

D3=intercept survey of 1034 casual users July 2011, provided by Transport for London.

D4=London travel demand survey, 56 671 adult London residents, 2005-09.[27]

D5=national travel survey, 10 949 adult London residents, 2005-09.[28]

D6=health survey for England, 2669 adult London residents, 2008.[29]

D7=UK burden of disease, 2010, provided by World Health Organization[30]; data then reweighted for size and demographic structure of population of cycle hire users.

D8=London specific life tables for 2008-10, provided by Office for National Statistics.

D9=Routino software (www.routino.org) used to identify routes on road and cycling network, derived from OpenStreetMap (CCBY-SA).

D10=London atmospheric emissions inventory 2008 concentration maps, for PM2.5.[31]

D11=police recorded road traffic crashes involving a cycle hire bicycle 2010-12 (STATS19), collated and provided by Transport for London.

D12=routinely collected police information on all road traffic crashes (STATS19) 2005-11.[32]

Table 2| **Cycle hire usage between April 2011 and March 2012**

Cycle hire usage	Registered users	Casual users	All cycle hire users
Total usage:	92 717	485 890	578 607
Total No trips	5 099 425	2 292 640	7 392 065
Total duration of use (h)	1 065 931	1 021 516	2 087 447
Average usage:			
Mean trips per user per year	55.00	4.72	12.78
1 or 2 trips per year (% (No) of users)	13 (7648)	55 (268 650)	51 (276 298)
Average duration per user per year (h)	11.50	2.10	3.61
Average trip duration (min/trip):			
All days	12.54	26.73	16.94
Weekdays	12.20	23.46	14.84
Weekend/holidays	14.16	30.93	23.06

Table 3| Estimated proportion (%) of total cycle hire travel time accounted for by men and women of different ages among past year users (n=578 607 individuals, between April 2011 and March 2012)

Age groups	Males	Females	Both sexes
≤14	0	0	0
15-29	21.4	13.7	35.1
30-44	32.5	10.5	43.0
45-59	15.2	4.2	19.4
60-69	1.7	0.5	2.2
70-79	0.2	0.1	0.3
≥80	0.01	0.01	0.01
All ages	71.0	29.0	100

See tables 2-5 in appendix 3 for derivation of these estimated percentages.

Table 4| Estimated modal shift associated with cycle hire use, and point estimates of exposures for each mode

Variables	Physical activity		Physical activity and air pollution	Air pollution		Modelled injury rates per million hours among 16-60 year olds (including scaling for under-reporting)					
	No (%) of trips (millions)*	Past year travel time (millions hours)	Median METs of activity	Average route exposure to PM2.5	Pollution exposure factor†	Killed, male	Serious injury, male	Slight injury, male	Killed, female	Serious injury, female	Slight injury, female
Observed:											
Cycle hire bicycle	7.39	2.09	6.8	15.75	6.8	0‡	6.30‡	30.80	0‡	9.28‡	16.70‡
Counterfactual modal shift:											
Own bicycle	0.51 (6.9)	0.12	6.8	15.75	6.8	0.20	11.42	76.46	0.55	9.02	63.07
Walking	2.26 (30.6)	0.90	3.3	14.51	2.64	0.09	2.74	10.14	0.07	1.84	8.92
Bus	1.34 (18.1)	0.53	1.5§	17.81	1.5	0.004	1.91	1.74	0.004	1.93	0.29
Underground	2.01 (27.2)	0.65	1.5§	200	0.825	0.002‡	0.47	Not used	0.002‡	0.47	Not used
Train	0.16 (2.1)	0.05	1.5§	14.91	1.5	0‡	0.05	Not used	0‡	0.05	Not used
Taxi	0.23 (3.1)	0.06	1§	17.80	1.3	0‡	0.74	13.16	0‡	0.60	6.11
Car or van	0.13 (1.8)	0.05	1.5§	17.80	1.95	0.02	1.28	19.30	0.02‡	1.14	18.19
Motorcycle/moped	0.04 (0.6)	0.01	2.5§	17.80	2.5	0.77	23.67	147.65	0.44‡¶	22.91¶	207.98¶
Other	0.04 (0.6)	0.02	1§	14.91	1	0	0	0	0	0	0
Trip newly generated by cycle hire	0.67 (9.0)	0	1	14.91	1	0	0	0	0	0	0

MET=metabolic equivalent of tasks; PM2.5=air pollution particles of diameter ≤2.5 µm; not used (that is, treated as zero)=no reliable data.

See appendix 3 for further details of the calculation of values presented in this table.

*The modal shift proportions presented correspond with the midpoint estimate of 9% of cycle hire trips being newly generated; variations in this percentage lead to the other modal shift values being scaled accordingly.

†Pollution exposure factor created by multiplying a scaling factor for ventilation rate, scaling factor for road position, and scaling factor for composition of pollution (see table 16 in appendix 3).

‡Should be treated with some caution as they are based on fewer than five fatalities or injuries.

§Not used for physical activity as median MET was ≤2.5 (marginal MET<=1.5)

¶Should be treated with particular caution as estimated denominator of time is more than 10 times smaller than for any other mode.

Table 5| Modelled health impact of cycle hire

Outcome by population	Specific diseases averted from changes in annual incidence (95% CrI)				All non-injury diseases (95% CrI)	Approach using observed cycle hire injury rates		Approach using background cycling injury rates for cycle hire	
	Ischaemic heart disease	Stroke	Depression	Others*		Injuries (95% CrI)	Total (95% CrI)	Injuries (95% CrI)	Total (95% CrI)
DALYs, modelled via specific diseases:									
Men	−41 (−61 to −24)	−15 (−23 to −9)	−8 (−37 to −1)	−16 (−29 to −6)	−83 (−120 to −56)	10 (4 to 20)	−72 (−110 to −43)	34 (21 to 51)	−49 (−88 to −17)
Women	−4 (−5 to −2)	−5 (−7 to −3)	−7 (−31 to −1)	−6 (−12 to −2)	−22 (−48 to −14)	6 (2 to 12)	−15 (−42 to −6)	21 (14 to 30)	−1 (−27 to 12)
Both sexes	−44 (−67 to −26)	−20 (−30 to −12)	−15 (−68 to −3)	−22 (−40 to −8)	−105 (−165 to −71)	17 (6 to 32)	−88 (−148 to −51)	55 (38 to 78)	−50 (−111 to −9)
YLLs (sensitivity 1†)									
Men	NA	NA	NA	NA	−73 (−131 to −41)	−3 (−4 to −2)	−76 (−134 to −44)	9 (3 to 15)	−64 (−122 to −31)
Women	NA	NA	NA	NA	−18 (−28 to −11)	−2 (−2 to −1)	−19 (−30 to −13)	14 (7 to 21)	−4 (−17 to 6)
Both sexes	NA	NA	NA	NA	−91 (−159 to −51)	−5 (−6 to −4)	−96 (−164 to −57)	23 (14 to 32)	−68 (−138 to −27)
YLLs (sensitivity 2‡)									
Men	NA	NA	NA	NA	−146 (−154 to −138)	−3 (−4 to −2)	−150 (−157 to −141)	9 (3 to 15)	−137 (−147 to −127)
Women	NA	NA	NA	NA	−32 (−34 to −30)	−2 (−2 to −1)	−34 (−36 to −32)	14 (7 to 21)	−18 (−25 to −11)
Both sexes	NA	NA	NA	NA	−178 (−188 to −168)	−5 (−6 to −4)	−183 (−193 to −173)	23 (14 to 32)	−155 (−169 to −141)

CrI=credible interval; DALYs=disability adjusted life years; NA=not applicable; YLLs=years of life lost. Negative values correspond to DALYs or YLLs gained—that is, a health benefit.

*Breast cancer, colon cancer, dementia, and diabetes, combined because impacts via these diseases were smaller. Point estimates are calculated separately for each cell from 50th centile of simulation (50 000 runs), as such estimates do not necessarily exactly sum (that is, estimates for men plus women may not exactly equal those for both sexes).

†Using Woodcock et al 2011.[16]

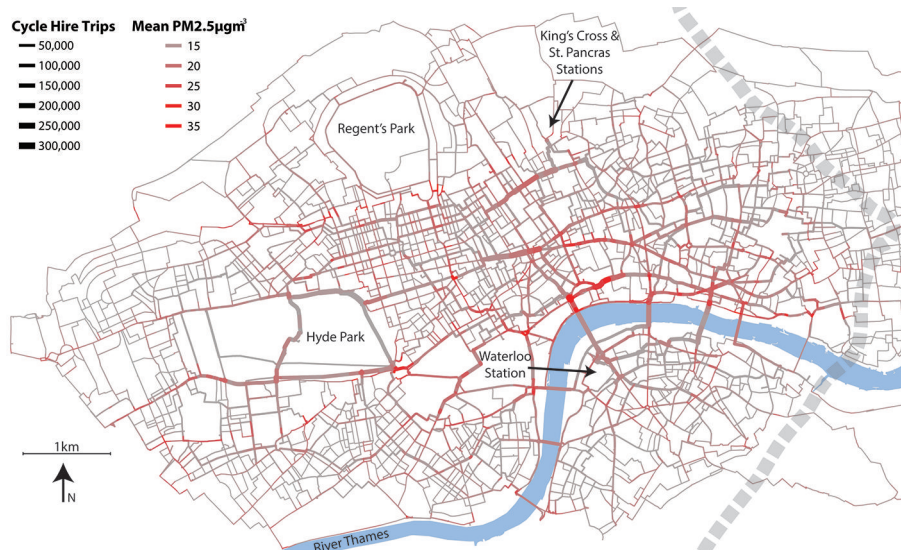‡Using Wen et al 2011.[17]

Figures

Fig 1 Map of cycle hire zone showing estimated number of cycle hire trips in past year along each route and average PM2.5 concentrations. The March 2012 eastern extension (dashed line) was only operational in final month of data collection, hence fewer trips in that area. See figure on bmj.com for full extent of eastern extension
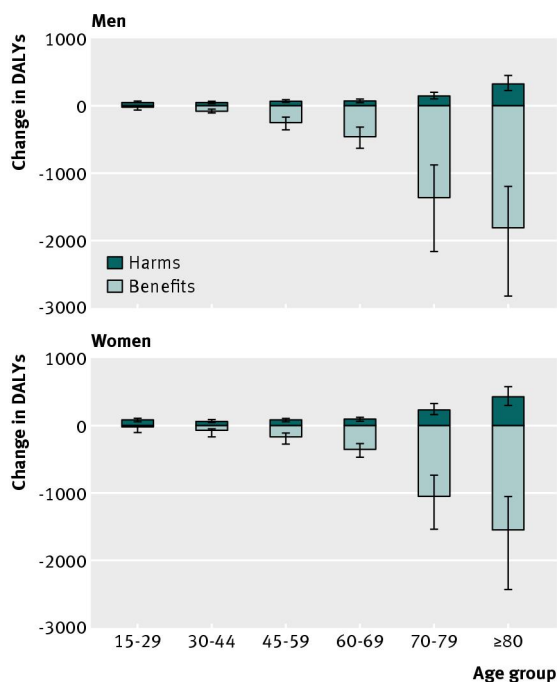

Fig 2 Trade-off of benefits to harms for cycling in central London: effects by age and sex, per million population (although few older people used cycle hire). Benefits come through impacts on diseases related to physical activity, harms come from exposure to road traffic injuries (see table 28 in appendix 4). Results use background injury rates and so should be interpreted as the trade-off for cycling in general in the cycle hire zone and not for specifically using cycle hire bicycles (which may carry lower risks of injury)
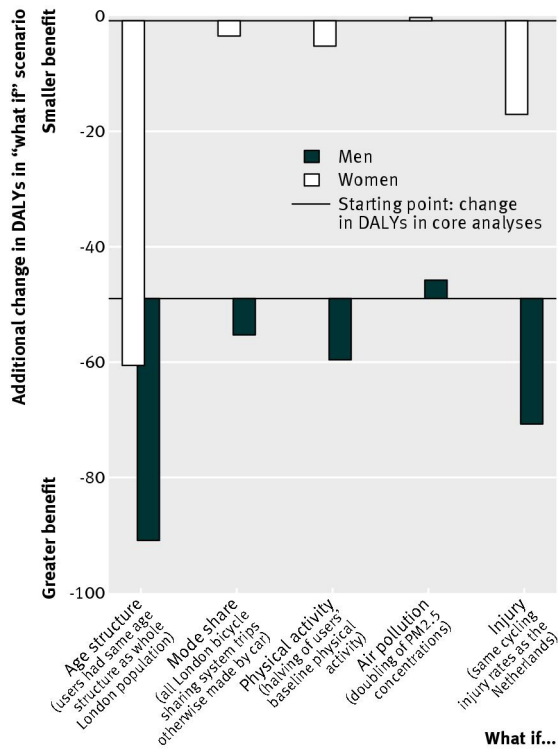
Fig 3 Deterministic sensitivity analysis, examining health impact of five "what if" scenarios