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Health, environmental and travel cost impacts of urban cycling

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Abstract

Cycling as a mode of transport avoids the negative external costs of driving such as air pollution, carbon emissions and noise and can also reduce the public health costs associated with physical inactivity. However, increased cycling may also have disadvantages such as increased exposure to air pollution and risk of traffic collisions. A number of studies have developed methods to quantify these health and environmental impacts and shown that the overall impact of increased cycling is positive. However, while minimising travel costs is traditionally the main objective of transport planners, these studies have not included travel cost impacts in their analyses. In this study, the impacts of a modal shift towards cycling are quantified, taking into account health, environmental as well as travel cost impacts. It was found that the health and environmental impacts of increased cycling in Dublin would be strongly positive, mainly due to health benefits of physical activity. When travel costs are also included in the analysis, the central estimate of net impact remains positive but the uncertainty increases considerably. This underscores the importance of the transport and health sectors working together to maximise the social welfare resulting from transport projects.

Keywords chosen from ICE Publishing list

Transport planning, Social Impact, Environment.

List of notation

POWSCAR	Place of Work, School or College – Census of Anonymised Records
POWCAR	Place of Work – Census of Anonymised Records
WHO	World Health Organisation
HEAT	Health Economic Assessment Tool
GDP	Gross Domestic Product
BOD	Burden of Disease
YLLs	Years of Life Lost
YLDs	Years of healthy Life lost to Disability
DALYs	Disability Adjusted Life Years
MET	Metabolic Equivalent of Task
IPAQ	International Physical Activity Questionnaire
RR	Relative Risk
VOLY	Value of a Life Year
VSL	Value of a Statistical Life
RSA	Road Safety Authority
STRADA	Swedish Traffic Accident Data Acquisition
AIS	Abbreviated Injury Scale
$PM_{2.5}$	Particulate matter with aerodynamic diameter of 2.5μm or less
EPA	Environmental Protection Agency

HEATCO	“Developing Harmonised European Approaches for Transport Costing and Project Assessment”, EU FP6 project, runtime 2004-2006
APHEIS	Air Pollution and Health: A European Information System
NO_x	Nitrogen Oxides
NMVOC	Non-methane volatile organic compounds
SO2	Sulphur dioxide
TREMOVE	Policy assessment model and transport and environmental database, owned by the European Commission
COPERT	A software tool used to calculate air pollutant and greenhouse gas emissions from road transport
IMPACT	“Internalisation Measures and Policies for All external Cost of Transport”, study on behalf of European Commission, runtime 2007-2008
GHG	Greenhouse Gas
CO2	Carbon Dioxide
GCoT	Generalised costs of travel
VoT	Value of Time
N	number of individuals in the population.
ΔYLL^i	change in expected YLLs due to condition *i.*
$YLL_B^{\ i}$	YLLs expected at baseline.
$METS_B$	MET hours of physical activity at baseline.
$RR_{Ref}^{\ i}$	reference RR associated with disease *i.*
$METS_{Ref}^{\ i}$	reference MET hours associated with disease *i*.
$METS_C$	additional MET hours of cycling.
λ^i	power transformation of the exposure.
ΔD_{PA}	change in deaths per year due to the cycling physical activity.
MR_B	baseline mortality rate.
RR_{Ref}	reference Relative Risk (RR) from the underlying studies in the HEAT meta-analysis
d_{Ref}	reference cycling distance from the underlying studies in the HEAT meta-analysis.
d	average distance cycled in the scenario of interest.
ΔI	change number of injuries per year.
I_B	number of injuries at baseline.
d_{s_B}	distance travelled by the striking mode in the study scenario.

d_v	distance travelled by the victim mode in the study scenario.
α and β	power transformations of the distance travelled which account for the non-linear relationship between road traffic injuries and distances travelled.
w	number of work days per year.
C, S, O and D	activities of driving, sleeping, cycling and other.
C_a	pollution concentration factor for activity *a*
T	i24 hours
ΔC_{Ref}	reference concentration change for condition *i.*
ΔC_{eq}	equivalent change in concentration of $PM_{2 \cdot 5}$.

Introduction

Encouraging cycling as a mode of transport has become a major goal of transport authorities and urban planners in many cities in the developed world. Cycling avoids the negative external costs of driving such as air pollution, carbon emissions and noise as well as the health consequences of physical inactivity, the 4th leading risk factor for global mortality (WHO, 2016). However, there are additional risks associated with cycling such as increased vulnerability to road traffic collisions and increased in-travel exposure to air pollution. Additionally, there are monetary costs associated with any measures to encourage cycling. All of these benefits and costs should be considered before taking action to increase levels of cycling in a city.

A number of studies have developed methods for quantifying the impacts of increasing uptake of active modes of travel and these have been described in two recent reviews (Doorley, Pakrashi, & Ghosh, 2015b; Mueller et al., 2015). The various impacts of active travel considered in these studies included the health impacts of physical activity and in-travel pollution exposure, changes in risk of traffic collisions and avoidance of environmental emissions. These results of these studies have shown that, overall, the benefits of cycling in cities outweigh the risks. However, there are still several important methodological issues to be addressed. For example, physical activity was consistently found to be the most significant impact in previous studies but there were significant variations in the models used to quantify the impact of the physical activity. Some studies also applied multiple models to the same scenario and found that the choice of model significantly affected the scale of the resulting impact (Doorley, Pakrashi, & Ghosh, 2015a; J. Woodcock, Givoni, & Morgan, 2013). In addition, no study to date has included the cost of travel itself alongside health and environmental impacts. Traditionally, travel costs have been the most important cost to be considered by transport planners and so their exclusion is a major concern.

This study develops a framework for comprehensively quantifying the impacts of a modal shift in favour of cycling, taking into account the health impacts of physical activity, air pollution and traffic collisions; the avoided environmental impacts of motorized travel; and the travel cost impacts. The health impacts are quantified using a Burden of Disease (BOD) approach. However, for comparison, the health impacts of the physical activity were also quantified using three mortality-based models. Conservative sensitivity analyses of all impacts were also carried out to determine upper and lower bounds for each impact.

The framework is applied to a case study of work commuters in Dublin. In the next section, the scenario of interest in the case study is described. This is followed by a descriptions of the various models used to estimate the total societal impacts in monetary terms. The results are then presented, followed by a conclusion.

2. Case Study of Dublin

The scenario of interest in this study was one whereby all work commuter trips currently undertaken by car or van which would be considered as cycle-able are cycled. This is clearly an idealized scenario but it allows indicative estimates of the relative scale of the various benefits and risks of cycling to be made. For this purpose, it was assumed that a journey of 5km or less each way is cycle-able. This was considered reasonable as a European study has suggested that cycling may be the fastest mode of transport for trips of 5 km or less in urban environments (European Commission, 1999). The data for this study was sourced from the POWSCAR (Place of Work, School or College – Census of Anonymised Records), 2011 data (Central Statistics Office, 2011a, 2011b). This dataset includes details of commuter trips made by all persons over the age of 4, resident in Ireland on Apr/10/2011, including home and work/school/college locations, journey times and journey modes. A summary of the daily work trips in county Dublin based on these data is shown in Table 1. Since POWSCAR, 2011 only specifies journey times; the journey distances were estimated using average driving speeds. Trips were categorized based on their origins and destinations as being city trips, outside-city or combined trips. For outside-city and combined trips, average journey speeds of 25km/hr and 21km/hr were estimated based on POWCAR (Place of Work – Census of Anonymised Records), 2006 (Central Statistics Office, 2006) which included both journey times and journey distances. For city trips, this method was not used because a speed limit of 30km/hr was introduced in Dublin city centre in 2010. A conservative average driving speed of 15 km/hr was assumed for city trips. Average cycling speeds was estimated to be 14km/hour, consistent with the assumptions of the WHO’s Health Economic Assessment Tool (HEAT) (WHO, 2014). The impacts of this modal shift were quantified for a single year—2012.

3. Estimation of Impacts

The impacts of increased cycling which were considered in this study included both those experienced by the cyclists themselves—health effects of physical activity, in-transit pollution exposure, traffic collisions and travel costs—and those experienced by the rest of society—traffic collisions, reduced emissions of air pollution and greenhouse gases, reduced noise and reduced congestion. Different models were used to quantify each of these impacts and convert them to equivalent monetary units. An outline of the methods used to quantify and monetise each impact is shown in Table 2 and each of these impacts is discussed in detail below. All monetary values from previous years were updated to 2015 values based on GDP per capita growth in Ireland (OECD Data, 2016). Since there are significant uncertainties associated with the models, upper and lower bounds are also calculated which take into account the main sources of uncertainty.

3.1 Health Impacts of Physical Activity

Cycling as a mode of travel is a physical activity which is typically performed at a moderate intensity and such activities have positive long-term health impacts. The benefits of physical activity can be quantified in terms of mortality or Burden of Disease (BOD). In this study, the BOD approach is taken because, it is more appropriate for quantifying the health impacts of chronic exposure to air pollution and physical activity than mortality-based approaches (Doorley et al., 2015b). BOD is a summary measure of the impact of a disease on health, taking into account both Years of Life Lost (YLLs) and Years of healthy Life lost to Disability (YLDs). The sum of YLLs and YLDs gives the total Disability Adjusted Life Years (DALYs) lost. To calculate the change in DALYs due to physical activity, the average kms cycled by the additional cyclists in each age and gender group were first converted to Metabolic Equivalent of Task (MET) hours using a compendium of physical activity MET factors (Ainsworth et al., 2011). A MET factor of 6.8 was used for cycling, consistent with HEAT for cycling. Non-travel related physical activity MET hours also needed to be estimated. The proportions of people in each age and gender group having a physical activity level of, low, moderate or high on the International Physical Activity Questionnaire (IPAQ) scale could be obtained from the results of the recent Health Ireland survey (IPSOS MRBI, 2015). The MET hours per week associated with low, moderate and high activity levels were estimated to be 0, 10 and 28 based on the IPAQ guidelines (IPAQ

Research Committee, 2005). The relationships between MET hours of physical activities and the risk of various health conditions were modelled based on a systematic review by J. Woodcock et al. (2009). The health conditions modelled were cardiovascular disease, breast cancer, colon cancer, dementia, depression and type II diabetes. It was assumed that the Relative Risks (RR) applied to both YLLs and YLDs. Similarly to J. Woodcock et al. (2013) , the RRs were adapted to the appropriate levels of physical activity in the current study by assuming a log-linear relationship between risk of each condition and a power of 0•5 transformation of MET hours (power of 0.375 for diabetes). The baseline expected YLLs and YLDs for each age and gender group were obtained from the WHO global BOD estimates for 2012 (World Health Organization, 2014). The new cyclists were grouped by age, gender and level of baseline activity and the change in YLLs for each group due to each condition, *i*, were calculated using Eq. 1 to Eq. 3.

$$\Delta YLL^{i} = N \times YLL_{B}{}^{i}\left(1 - \frac{RR_{C}{}^{i}}{RR_{B}{}^{i}}\right) \tag{1}$$

$$RR_{C}{}^{i} = RR_{Ref}{}^{i} \wedge \left(\frac{METS_{C} + METS_{B}}{METS_{Ref}{}^{i}}\right)^{\lambda^{i}} \tag{2}$$

$$RR_{B}{}^{i} = RR_{Ref}{}^{i} \wedge \left(\frac{METS_{B}}{METS_{Ref}{}^{i}}\right)^{\lambda^{i}} \tag{3}$$

The change in the expected YLDs was calculated in the same way. The sum of all DALYs saved across all groups gave the central impact for total DALYs saved due to physical activity. This impact could be represented by a monetary value by multiplying the number of DALYs saved by the Value of a Life Year (VOLY). A VOLY of €94,794 was used based on an Irish study (Deloitte Access Economics, 2011). To calculate upper and lower bounds based on this model, the analysis was repeated, replacing the reference RRs with limits of the 95% confidence intervals as reported by J. Woodcock et al. (2009).

Since previous studies have shown that physical activity is the most important determinant of the impacts of cycling and also that the choice of model can have a significant effect on the results, some additional analysis of this impact was carried out for comparison using three different models: quantifying deaths using the 2014 version of the Health Economic Assessment Tool (HEAT) for cycling; quantifying YLLs using HEAT 2014; and quantifying deaths using the 2011 version of the HEAT. The HEAT for cycling is the most widely used model for quantifying the mortality impacts of the physical activity of cycling. The first secondary model of this study was based on the most recent version of this tool, released in 2014, which predicts the decrease in all-cause mortality due to increased cycling in a population after a build-up period of 5 years based on Eq. (4).

$$\Delta D_{PA} = N \times MR_B \times \left(1 - RR_{Ref}\right) * \left(\frac{d}{d_{Ref}}\right) \tag{4}$$

Baseline mortality rates associated with each 5-year age group in Ireland were obtained from the WHO Mortality Database (WHO, 2016). The resulting avoided fatalities were converted to an equivalent monetary value using the Value of a Statistical Life (VSL). The VSL of €5,128,420 suggested by the WHO for use in Ireland was used. As with the main model, the limits of the 95% confidence interval for the reference RR were used to calculate upper and lower bounds. In another secondary model, the RRs estimated using the HEAT, 2014 model were applied to the baseline all-cause YLLs per year to find the change in YLLs per year as a result of the physical activity. The economic impact of this reduction in YLLs was estimated using the VOLY. As with the main model, the limits of the 95% confidence interval for the reference RR were used to calculate upper and lower bounds. The final secondary model was based on the 2011 version of HEAT, 2011. This older version of HEAT, released in 2011, has been widely used and discussed in studies which assessed the benefits and risks of cycling (Deenihan & Caulfield, 2014; Rojas-Rueda, de Nazelle, Tainio, & Nieuwenhuijsen, 2011; Rojas-Rueda, de Nazelle, Teixido, & Nieuwenhuijsen, 2012) before the 2014 version was released. However, the base of epidemiological evidence for HEAT, 2011 was not as comprehensive as that of the 2014 version (WHO, 2014).

3.2 Traffic collisions

In this study, the change in the incidence of fatal and non-fatal collisions for each mode in response to the modal shift was modelled by using a non-linear model similar to that used by J. Woodcock et al. (2013). For each pairwise combination of striking mode and victim mode, the number of fatal injuries and the number of non-fatal injuries were calculated using Eq. (5):

$$\Delta I = I_B \times \left(\left\{ \frac{d_s}{d_{s_B}} \right\}^{\beta} \times \left\{ \frac{d_v}{d_{v_B}} \right\}^{\alpha} - 1 \right) \tag{5}$$

The power transformations α and β vary by mode and were obtained for this study from Elvik (2009) and J. Woodcock et al. (2013). The baseline distances travelled by each mode were estimated using a similar method to Short and Caulfield (2014). The baseline collision data was obtained from the Road Safety Authority (RSA) Road Collision Factbook 2011 and 2012 (Road Safety Authority, 2011, 2012). It was assumed that the apportionment of non-fatal injuries to victim-striking mode combinations in Dublin County was the same as in Ireland as a whole. It was also assumed that the ratio of serious injuries to minor injuries for each combination of modes in Dublin was the same as the ratio of serious injuries to minor injuries in Ireland as a whole.

It is well documented that traffic collisions are significantly underreported, particularly minor collisions and collisions involving active modes. In Ireland the road collision information accumulated by the RSA is based on reports by the police service, An Garda Síochána. One study has estimated that the true number of cycling collisions in Ireland is six times greater than the police reported number (Short & Caulfield, 2014). In order to account for such underreporting, the baseline collision data from RSA was scaled using mode and severity specific correction factors provided by the HEATCO study (Bickel et al., 2006). The scaled and unscaled results provided upper and lower bound estimates for the change in traffic collision casualties and the average of these was taken as the central estimate.

In order to represent the change in traffic collisions in monetary terms, it was necessary to first estimate the resulting change in DALYs. The monetary cost could then be quantified based on the VOLY. It was assumed that the DALYs lost due to a fatal injury would be equal to the remaining life expectancy of the casualty at the time of the collision. The average DALYs per fatal collision was therefore assumed to be equal to the average remaining life expectancy among the 20-64 age group in the population of Dublin (CSO, 2015). This resulted in an average of 42.5 DALYs lost per collision. To estimate the YLDs lost due to serious and minor injuries, no suitable data from Ireland was available so reference was made to a recent study which estimated YLDs lost in traffic collision injuries based on data from the Swedish Traffic Accident Data Acquisition (STRADA) database. Values were estimated for each injury severity on the Abbreviated Injury Scale (AIS): minor, moderate, serious, severe, critical and maximal. The RSA collision statistics in Ireland do not clarify what is meant by a “serious” or “minor” injury or how these relate to the AIS so it was assumed that RSA minor injuries include those which would be classified as minor or moderate on the AIS and RSA serious injuries include those which would be classified as serious, severe, critical or maximal on the AIS. To estimate the YLDs lost for each RSA injury type, a weighted average was taken of the estimated YLDs for each corresponding AIS injury type, where the weighting was based on the relative frequency of these injury classes in STRADA.

3.3 Health Impacts of In-travel Pollution Exposure

Although pedestrians and cyclists do not produce air pollution while travelling, they are exposed to higher inhalation doses of toxic pollutants, mainly due to their elevated ventilation rates (McNabola, Broderick, & Gill, 2008; Panis et al., 2010; Zuurbier et al., 2010). $PM_{2.5}$ is commonly considered as the most important pollutant for predicting the long term health impacts of traffic related air pollution (Chen, Goldberg, & Villeneuve, 2008). To estimate the impact of the increased inhalation dose of travellers switching from car travel to active travel, an approach similar to Hartog, Boogaard, Nijland, and Hoek (2011) was taken. First, the ratio of yearly inhaled dose of $PM_{2.5}$ between the hypothetical and baseline scenarios was calculated. The ratio of inhalation doses, Rd was calculated using Eq. (6):

$$R_d = \left(\frac{w}{365}\right) \times \frac{C_C \times t_C \times MET_C + t_S \times MET_S + \left(T - t_A - t_S\right) \times MET_O}{C_D \times t_D \times MET_D + t_S \times MET_S + \left(T - t_D - t_S\right) \times MET_O} + \left(\frac{1-w}{365}\right) \quad (6)$$

The concentration factor accounts for the relative exposure concentration experienced by different modes using the same routes due to vehicle type and road position. Similarly to a recent study (James Woodcock et al., 2014), concentration factors of 0.8, 1 and 1.3 were used for pedestrians, cyclists and drivers respectively based on a systematic review of air pollution exposure by different modes of transport in Europe. The MET factors, sourced from a compendium of MET factors (Ainsworth et al., 2011) were used to account for the relative ventilation rates between each travel mode. For non-travel time, a concentration factor of 1 and MET factors of 0.95 for sleeping (8 hours) and 1.5 for the rest of the day were assumed, similarly to James Woodcock et al. (2014). It was then assumed that the health impact to these travellers of the increase in inhaled dose would be equivalent to the impact of an increase in average ambient $PM_{2.5}$ concentration of the same proportion. The baseline average annual PM2.5 concentration used for this calculation was estimated at 10µg/m^3 based on the EPA of Ireland Air Quality Report 2012 (Environmental Protection Agency, 2012). The health impacts of changes in ambient $PM_{2.5}$ concentrations have been studied extensively. In this study, the results of the APHEIS (Air Pollution and Health: A European Information System) study (Boldo et al., 2006) were used to estimate the changes in YLLs from cardiorespiratory diseases and lung cancer of the new cyclists due to their change in $PM_{2.5}$ exposure. This study found that a 10 µg/m^3 increase in mean $PM_{2.5}$ concentration was associated with RRs of 1.09 and 1.14 for cardiopulmonary and lung cancer mortality respectively. The change in YLLs could be modelled using Eq. 7 and Eq. 8:

$$\Delta YLL^i = N \times YLL_B{}^i \left(1 - RR_C{}^i\right) \quad (7)$$

$$RR_C{}^i = RR_{Ref}^i {}^{\Delta C_{eq} / \Delta C_{Ref}} \quad (8)$$

Since cardiovascular disease risk is influenced by both physical activity and pollution exposure, the impacts of the two exposures were modelled multiplicatively. To calculate upper and lower bounds based on this model, the analysis was repeated, replacing the reference RRs with limits of the 95% confidence intervals from the APHEIS study (Boldo et al., 2006).

3.4 External Pollution Impacts

The impacts of the decrease in toxic air pollution attributable to the reduction in vehicle km travelled was quantified in two steps. First, the reduction in emissions of $PM_{2.5}$, nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC) and sulphur dioxide (SO_2) were estimated and then the external impacts of these reductions were estimated. In the first step, estimates of the average emissions of each pollutant per km travelled by the Irish fleet were obtained from the TREMOVE v3.3.2 (Breemersch et al., 2010) database, a widely used source of aggregate emission factors based on COPERT v4 (Gkatzoflias, Kouridis, & Nlziachristos, 2007). The avoided emissions of each pollutant in the study scenario could then be easily calculated based on the avoided vehicle km (vkm) travelled. The external impacts of these avoided emissions were calculated by reference to the updated IMPACT Handbook (Korzhenevych et al., 2014). The Handbook gives cost estimates per tonne of each pollutant, differentiated by country as well as by type of locality—rural, suburban or metropolitan. It was assumed that emissions from city trips were 100% urban. For the central estimates, trips which had one end in the city centre were assumed 50% urban and 50% suburban and trips with both ends outside of the city centre were assumed 50% suburban and 50% rural.

To estimate the avoided cost of greenhouse gas (GHG) emissions due to the avoided vehicle km, the updated IMPACT Handbook was referenced again. The Handbook provides per-km GHG costs based on an avoidance cost per tonne of CO_2 equivalent of €90, corresponding to efforts required to stabilise global warming at 2°C. The costs are differentiated by fuel type, technology class, engine size and locality type. In order to calculate the average per-km GHG cost of the Irish fleet, the apportionment of the Irish fleet to each fuel, technology class and engine size therefore needed to be estimated. This was estimated using the Irish Bulletin of Vehicle and Driver Statistics (Department of Transport Tourism and Sport Ireland, 2012). Trips were allocated to metropolitan, suburban and rural as described above.

The avoided costs of noise pollution were also calculated using the updated IMPACT Handbook (Korzhenevych et al., 2014). Costs estimates are provided by locality and by type of traffic—thin or dense. For the central estimate, the average of the per-km cost estimates for dense and thin traffic was used.

In estimating each of the external pollution impacts, the allocation of trips to locality types and traffic levels was a significant source of uncertainty. Therefore, these choices were varied in calculating the lower and upper bound estimates. For all the lower bound estimates, trips with one end in the city centre were assumed 100% suburban and trips with both ends outside of the city centre were assumed 100% rural. For the upper bound estimates, trips with one end in the city centre were assumed 100% urban and trips with both ends outside of the city centre were assumed 100% suburban. In calculating the lower and upper bound estimates of avoided noise costs, traffic was assumed to be dense and thin respectively. Additionally, for the lower and upper bound avoided GHG cost estimates, the lower and upper bound unit costs per tonne of CO2 equivalent (€48 and €168) were used. The assumptions made regarding avoided external costs and the resulting unit costs values used for the central, lower and upper estimates are shown in Table 3.

3.4 Travel Costs

A modal shift from driving to cycling changes the travel time of the new cyclists but may also affect the travel time of others due to a reduction in congestion. In this study, generalised costs of travel (GCoT) were assumed to be a combination of time expended in traveling and vehicle operating costs. For drivers, a Value-of-Time (VoT) of €19/hr and car operating cost of €0.103/km were assumed, consistent with the National Transport Model (National Roads Authority, 2014) of Ireland. The VoT for cyclists has not been studied extensively but a Swedish study (Börjesson & Eliasson, 2012) has estimated the VoT for cycling on streets and on cycle paths respectively to be greater than the VoT of the next preference mode by factors of 1.83 and 1.21. As cyclists in Dublin use a combination of shared streets and cycle paths, the driving VoT was scaled by the average of these two factors to estimate the cycling VoT. For the upper bound and lower bound estimates, the cycle-path factor and the on-street factor were used respectively.

The external congestion costs were estimated based on the updated IMPACT Handbook which provides per-km marginal congestion costs differentiated by locality type, road type, and current congestion level—free flow, near capacity or over capacity. The same assumptions regarding locality type described for the external pollution impacts were used. The average of the unit costs for main roads near-capacity and other roads near-capacity was used for each locality type. For the upper and lower bound estimates, the locality type was varied as for the external pollution impacts. Also, for the upper bound estimate, it was assumed that all roads were over-capacity. For the lower bounds, it was assumed that suburban and rural roads were at free-flow. The unit congestion costs used can be seen in Table 3.

4. Results and Discussion

The impact of the study scenario on the numbers of cycling commuters and the vehicle kms avoided are shown in Figure 1 and Figure 2. Figure 1 shows that there were more females than males driving for trips inside Dublin City and outer Dublin County which could be cycled. Figure 2 also shows that the conversion to cycling of trips by females led to a greater number of vehicle km avoided than conversion of trips by males. For both males and females, the greatest potential for conversion of car trips was in the 25-29 and 30-34 age groups. The youngest and oldest age groups had the lowest potential for trip conversion. In terms of location, there was greatest potential for avoidance of vehicle kms in outer Dublin County. Trips between Dublin City and Dublin County had the lowest potential for conversion to cycling and avoidance of vehicle kms.

Figure 3 summarizes the health and environmental impacts of the modal shift envisioned in this study. Clearly, the positives outweigh the negatives and in particular, the physical activity benefits are significantly greater than any of the other impacts. This result is consistent with previous studies into the health and environmental impacts of increased cycling (Doorley et al., 2015b; Mueller et al., 2015). The secondary analysis of the physical activity benefits produced even more positive results. As shown in Figure 4, both of the models based on HEAT 2014 predicted significantly higher benefits of physical activity than the main BOD model. More surprisingly, the HEAT, 2011 model predicted benefits approximately five times greater than the main model. Previous studies have shown that different models of the health impacts of physical activity can produce significantly results but this is the first study to have compared both versions of HEAT. The model which used the RRs from HEAT, 2014 to quantify the change in YLLs was slightly more conservative than the model which quantified deaths based on HEAT, 2014 model. However, the influence of quantifying YLLs rather than fatalities was much less dramatic than the influence of using a different model to calculate the RRs. In the analysis that follows, only the results of the BOD model are considered in order to maintain consistency with the other health impact estimates and because these were the most conservative estimates. The only one of the impacts which was significantly negative was the change in road traffic collisions. Further insights can be gained by examining the predicted changes in traffic collisions for individual combinations of striking mode and victim mode. As shown in Table 4, there was a decrease in the total car driver fatalities and non-fatal casualties. There was also a decrease in the number of fatalities where cars were the striking vehicles. Total pedestrian fatalities and non-fatal casualties both decreased despite an increase in pedestrians being injured by cyclists. All of these results can be attributed the reduced distances driven by cars in the road network. However, for cyclists, the numbers of fatal and non-fatal victims were both increased. This increase in cycling casualties was much more significant than the reductions in driver and pedestrian casualties. Of particular concern is the large increase in the number of non-fatal cyclist injuries. Clearly, the benefits of the reduction in vehicle kms driven and the “Safety in Numbers” effect were not sufficient to offset the relative vulnerability of cyclists to traffic collisions. The scale of the cost of minor cyclist casualties is particularly concerning due to the high level of underreporting of this type of incident. If underreporting of minor cyclist injuries is not accounted for when considering projects to promote cycling, the benefits of such projects may be significantly overestimated.

The only other negative impact of the increased cycling in this study was due to the in-travel pollution exposure of cyclists and the scale of this impact was insignificant when compared to the physical activity and traffic collision impacts. However, it is worth noting that the pollution exposure estimates were not based on measured concentrations but on a simple exposure model which did not take into account variability due to traffic levels, time of day or available cycling facilities.

As shown in Figure 5, the positive external impact of reduced air pollution was of a similar scale to the negative individual pollution exposure impact. The benefit of the reduction in GHGs was the greatest environmental impact. The uncertainty in the value of the GHG reduction is high due to the uncertainty in the per-tonne avoidance cost of a CO_2 equivalent. The value of the external noise reduction was greater than the value of the avoided air pollution, despite air pollution usually receiving much more attention than noise as a negative impact of motorised transport.

Up to this point, only the health and environmental impacts of cycling have been considered, similarly to most recent studies into the benefits and risks of cycling. As shown in Figure 6, the travel time impacts to both the cyclists and other travellers are very significant in the study scenario, but as the increase in GCoT of the cyclists is almost equal to the decrease in congestion costs as a whole, there is little change in the central estimate of the total net impact. However, there is considerably uncertainty in both estimates, particularly with regard to the VoT associated with time spent cycling. This causes the lower estimate of the total net impact to be negative. No previous studies of the total benefits and risks of cycling have predicted negative net impacts, even in sensitivity analysis. However, no previous studies have considered GCoT in their calculations, despite this being traditionally the most important cost to consider in appraising transport projects.

4. Conclusion

Overall, it can be firmly concluded that the health and environmental impacts of increased cycling in Dublin would be strongly positive. Although in this study, the different models for the physical activity impacts produced significantly different results, the net benefit was positive even with the most conservative physical activity model. When travel costs are also considered, the uncertainty becomes greater but the best estimate of the net impact is still positive. The largest sources of uncertainty are related to the marginal congestion of travel by car and the VoT associated with cycling. In future studies, the uncertainty regarding congestion could be reduced by using a bottom-up estimation based on speed-flow curves or simulations for the study area (Korzhenevych et al., 2014). Estimates of the cycling VoT could be improved by means of choice modelling experiments with the local population.

The methods and results of this study may be useful to transport planners who are considering measures to encourage cycling in order to improve public health and reduce environmental pollution and congestion. However, it should also be noted that these results do not address the possibility that the benefits and risks of cycling are unevenly spread across participants of different demographics and that some sub-populations of cyclists may even experience a net negative impact. The benefits and risks experienced by cyclists in different demographic groups are relatively unexplored and require further research.

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Tables and Figures

Table 1 Commuter trips by car/van, bicycle, walking and public transport (PT) in county Dublin as per census, 2011

Table 2 Outline of models used to quantify and monetise impacts of active travel

Table 3 Unit costs for avoided external impacts

Table 4 Change in traffic collision casualties.

Figure 1 Commuters converted from driving to cycling

Figure 2 Vehicle km avoided by converting trips from driving to cycling

Figure 3 Summary of health and environmental impacts. Bars indicate upper and lower bounds.

Figure 4 Comparison of models for health impact of physical activity

Figure 5 Summary of less significant impacts of cycling uptake.

Figure 6 Summary of health, environmental and travel-cost impacts.

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