ARTICLE IN PRESS

Journal of Transport & Health xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Transport & Health

journal homepage: www.elsevier.com/locate/jth

Health impacts of cycling in Dublin on individual cyclists and on the local population

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ABSTRACT

There is an emerging consensus that personal and societal health benefits in cycling largely outweigh the risks. However, there exists limited research into the health impacts experienced by individuals who take up cycling or the marginal societal benefits resulting from incremental uptake of cycling. This paper models and estimates the health impacts of individuals in Dublin taking up cycling. The paper utilizes the 2011 census data of Ireland and a Burden of Disease (BOD) approach is used to estimate health impacts on the individuals taking up cycling for their regular commute and on the rest of the local population separately. The health impact to an individual changing from private car to cycling ranged from a benefit of 0.033 Disability Adjusted Life Years (DALYs)/year to a loss of 0.003 DALYs/year. The marginal health impact to the local population ranged from no change to a benefit of 0.006 DALYs/year. Increases in cycling have a consistently positive impact on the health of the local population, regardless of the current modal split. The net expected health impacts to the individual cyclists are also positive in most cases. However, for some individuals in the 20–29 age group, the expected health impact may be small to negative, mainly due to a higher traffic collision risk. Where total impacts of scenarios are modelled the potential negative health impacts to some individuals may be masked by the overall positive health benefits of cycling to the local population. When promoting cycling as an alternative to driving to improve population health impacts, the risks to some cyclists should be managed and mitigated through safe road systems approaches.

1. Introduction

The choice of travel mode is one which has significant health impacts not only to the individual traveller but also on the rest of society. This is particularly true in the case of cycling which brings about considerable physical and mental health benefits for the cyclists and also benefits the rest of the local population through avoidance of toxic emissions and other negative impacts of motorised transport. Largely due to these benefits, commuting by bicycle has been actively promoted in recent years by both researchers and governments as a way for individual's to improve their own health with co-benefits for the rest of society (Lavin et al., 2011; Teschke et al., 2012). However, individuals who cycle are also exposed to increased air pollution doses and increased risk of traffic collision. Therefore, if switching from driving to cycling is to be encouraged for the accompanying health benefits, it is important that all of the health benefits and risks can be quantified in common units in order to ensure that the expected net impact to the individual cyclist is positive. A number of recent studies have developed methods for quantifying the total health benefits of increases in cycling, motivated by a need for transport planners to take these benefits into account when making decisions (Doorley

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http://dx.doi.org/10.1016/j.jth.2017.03.014
Received 26 August 2016; Received in revised form 8 March 2017; Accepted 10 March 2017

et al., 2015b; Mueller et al., 2015). These studies have used a variety of methods to estimate the total expected change in mortality (Deenihan and Caulfield, 2014; Hartog et al., 2011; Rojas-Rueda et al., 2011; Rojas-Rueda et al., 2012) or Burden of Disease (BOD) (Maizlish et al., 2013; Rojas-Rueda et al., 2013; Woodcock et al., 2009; Woodcock et al., 2013) of real or hypothetical large-scale modal shifts and the consensus has been that the health benefits tend to far outweigh the health risks. However, this type of approach has limited value in understanding the decisions and experiences of individual transport users for a number of reasons. Firstly, if the outcome of interest is total expected change in mortality or BOD—including the individual health impact on the cyclist and the external impact on the local population—a positive result does not necessarily indicate that the expected health impact for the individuals who switch from driving to cycling is positive. It is possible that expected external benefit simply outweighs the expected damage to the health of the cyclists. Secondly, the benefits and risks may be unevenly distributed across different demographic groups so that some groups of cyclists experience positive impacts on average while others experience negative impacts. Finally, changes in modal split (proportions of trips in the network using each transport mode) happen incrementally and the marginal health impacts (health impacts resulting from a unit increment) of motorised transport use are generally not equal to the average health impacts (Korzhenevych et al., 2014) because these health impacts are influenced by the current modal split. Therefore, the expected individual and marginal external impacts of each individual switch from driving to cycling can be expected to be different from each other and from the averaged impact of a large cohort switching to cycling. Quantifying the individual and marginal external impacts of switching to cycling at the level of individual decisions has not been attempted in the literature to date and requires a different approach to those used to quantify total societal impacts.

The present study aims to determine whether or not the benefits to an individual taking up cycling in Dublin outweigh the risks for all ages, genders and trip lengths. Another objective is to examine how the individual and marginal external impacts of each additional cyclist vary with the overall level of cycling modal share. A model is developed for estimating both the individual and marginal external impacts of a single user unilaterally switching from driving to cycling for their commute in various modal splits, taking into account age and gender specific effects. A clear distinction is made between the impacts experienced by the individual cyclist and by the rest of society. This study focusses on health impacts only as these are highly variable across age and gender and they have been the focus of much interest in the literature to date. Burden of Disease (BOD) is a summary measure of the impact of a particular health risk such as a disease on global health which takes into account both years lost and years spent in poor health. The BOD approach is used to quantify health impacts in this study because age and gender specific variations are key considerations in this study and BOD takes into account the life expectancy at the time of death.

The procedure described in this study also takes a different approach to uncertainty analysis by sampling key model parameters from appropriate probability distributions. In this way, the analysis accounts for variations in individual characteristics as well uncertainties in the health impact models.

2. Methods

2.1. Scenario design

In this study, the range of health impacts resulting from an individual—the test subject —switching from driving to cycling are quantified using health impact models from the literature. The approach used involves defining a reference scenario where the test subject drives and a test scenario where the test subject cycles and quantifying the difference in expected BOD outcomes between these scenarios. This process is repeated many times for different test subjects and modal splits. The procedure can be described as follows. Three modal split (MS) stages were first defined:

- The Current MS: the modal shares of walking, cycling, private car and public transport for commuter trips are 14·5%, 5·8%, 56·1% and 22·4% respectively as per the 2011 census (Central Statistics Office, 2011).
- The Smarter Travel MS: the modal shares of walking and public transport remain at 14·5% and 22·4% but the modal share of cycling has increased to 10% while private car share has fallen to 51·9%. This represents the achievement one of the goals of the National Cycle Policy Framework 2009–2020—to have 10% of work trips made by cycling (Smarter Travel, 2009).
- The Intermediate MS: the modal shares of walking and public transport remain at 14·5% and 22·4% and the modal shares of cycling and private car are halfway between those of the Current and Smarter Travel MSs—7·9% and 54% respectively.

The three scenarios are assumed with the intention of presenting ‘do nothing’, ‘do minimum’ and ‘do something’ options as considered in a traditional cost-benefit analysis paradigm. The procedure that follows was repeated for each of the three MS stages as the target MS. The basic procedure was to create a reference scenario (RS) in which the target MS has been realised and a test scenario (TS) which only differed from the RS in that one additional private car user has switched to cycling for their commute. The individual and marginal external benefits of the additional cycling are then estimated by finding the difference between the health impacts in each scenario. The procedure was repeated multiple times to produce distributions of estimates, illustrating the influence of individual characteristics and the uncertainties in the models for estimating the impacts. The scenarios were informed by the POWSCAR (Place of Work, School or College – Census of Anonymised Records), 2011 data (Central Statistics Office, 2011). This dataset includes details of commuter trips made by all persons over the age of 4, resident in Ireland on 10/Apr/2011, including home and work/school/college locations, journey times and journey modes. 412,858 respondents were found to make a regular commute in the county of Dublin. Similarly to a previous study (Doorley et al., 2015a) journey distances were estimated based on reported journey times and estimated average driving speeds and it was assumed that current driving trips of 6 km or less each way can be

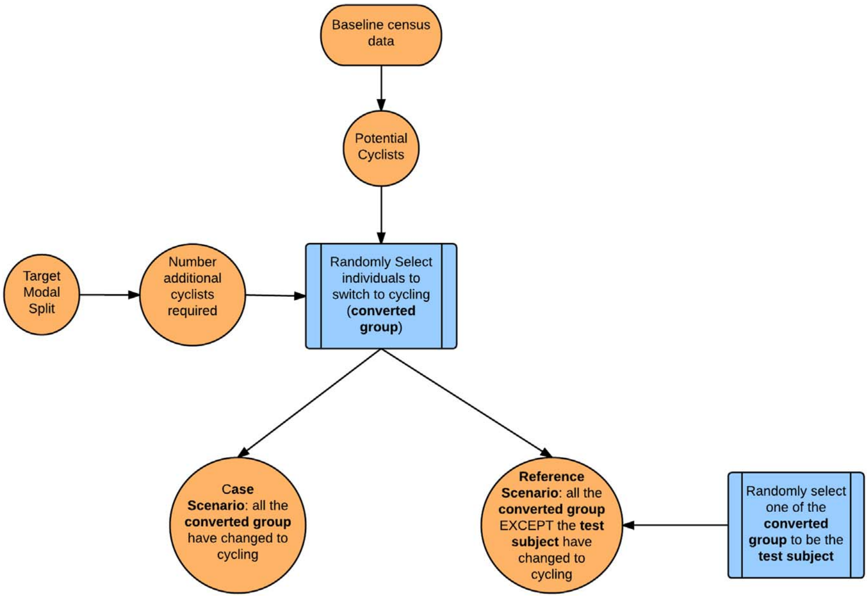

Fig. 1. Process for defining the Reference Scenario and Case Scenario.

considered as cycle-able trips. Some advantages of this type of dataset are that a large portion of the actual commuters in Dublin are captured and the data are highly reliable. Some disadvantages are that other useful information such as trip chaining and propensity to cycle are not captured. For this reason, it was necessary to make the simplifying assumption that any driving trip of less than 6 km could potentially be cycled. The following steps were carried out in Matlab (The Mathworks Inc., 2016) as illustrated in Fig. 1:

1. From the census respondents aged 20 to 64 who make cycle-able trips to and from work by private car, randomly select (with equal selection probability and without replacement) the required numbers of individuals to switch to cycling in order to meet the target MS. These individuals are assigned to the Converted group. In the case of the Current MS, a single individual is selected to switch to cycling and is the only individual added to the Converted group. Call the scenario in which the entire Converted group has made the change to cycling the Case scenario (CS).
2. Randomly select a single test subject from the Converted group. Call the scenario in which the entire Converted group except for the test subject makes the change to cycling the Reference Scenario (RS).
3. Calculate the individual health impacts to the test subject as a result of switching to cycling during one year by estimating the difference in expected DALYs lost by that individual between the CS and RS. Three determinants of individual health impacts were considered: physical activity (PA), individual exposure to air pollution during transit (AP_{In}) and traffic collision risk (TC_{In}). The details of these calculations are presented in the next section.
4. Calculate the expected marginal health impacts to the rest of the population in the study area as a result of the test subject switching to active travel during one year by estimating the difference in DALYs lost by the rest of the population between the CS and the RS. Two determinants of marginal external health impacts were considered: reductions in external air pollution (AP_{Ex}) and traffic collision risk (TC_{Ex}). The details of these calculations are presented in the next section.
5. Repeat steps 1 to 4 for 50,000 iterations. This number was considered appropriate because increasing the iterations by an order of magnitude did not make any appreciable difference to the results.

2.2. Modelling of health impacts

All health impacts in this study were modelled using a Burden of Disease (BOD) approach. BOD is a summary measure of the impact of a disease on health, taking into account both Years of Life Lost (YLLs) per year and the Years of healthy Life lost to Disability (YLDs) per year. The sum of YLLs and YLDs gives the total Disability Adjusted Life Years (DALYs) lost. In this study, the health impact to an individual or group was defined as the change in the statistical expectation of DALYs lost by that individual or group in a single year. The calculation of the change in DALYs associated with each of the individual determinants considered in this study is illustrated in Fig. 2 and discussed in detail below.

2.3. Health impacts of physical activity

The additional kms cycled by the test subject in the CS were 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 the Health Economic Assessment Tool for cycling (Who, 2014) and several recent studies (Maizlish et al., 2013; Woodcock et al., 2013;

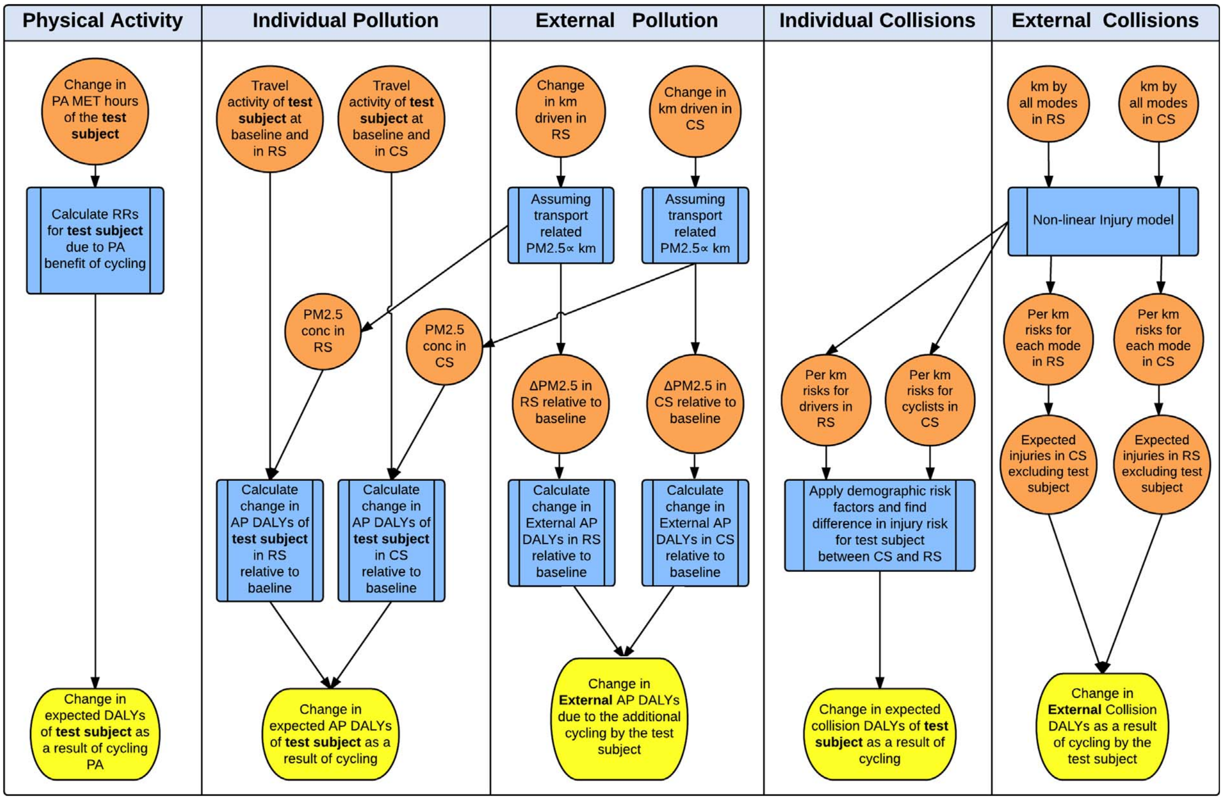

Fig. 2. Process for calculating the difference in health impacts between the Reference Scenario (RS) and Case Scenario (CS).

Woodcock et al., 2014). Non-travel related physical activity MET hours also needed to be estimated. The probability of an individual 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). At each iteration, the activity level of the test subject was sampled from a discrete distribution based on these probabilities. 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 based on a systematic review by Woodcock et al. (2009). For each health condition and iteration, a reference relative risk (RR) was sampled from a lognormal distribution with mean and 95% confidence interval (CI) equal to the mean and CI found in the review. Lognormal distributions are appropriate because RRs are ratios and so the log of a RR is normally distributed. The health conditions modelled were cardiovascular disease, breast cancer, colon cancer, dementia, depression and type II diabetes. No confidence intervals were available for the RR of depression, so the mean RR was used directly. It was assumed that the RRs applied to both Years of Life Lost (YLLs) and Years of healthy Life lost to Disability (YLDs). The RRs of this review were based on specific levels of weekly PA and so they needed to be adapted to the appropriate level of PA for each test subject in the current study. Similarly to Woodcock et al. (2009), this was achieved by assuming a log-linear relationship between risk of each condition and a power of 0·5 transformation of MET hours. For diabetes, a power transformation of 0·375 was used. The baseline expected YLLs and YLDs of the test subject for a given year were assumed to be equal to the per-capita YLL and YLD rates of the same age and gender group in Ireland in 2012 which were obtained from the WHO global BOD estimates for 2000–2011 (World Health Organisation, 2013). The change in the expected YLLs of the test subject due to each condition, i, was calculated using Eqs. (1)–(3).

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

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

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

Where ΔYLL^{i} is the change in expected YLLs due to condition i, $YLL_{B}{}^{i}$ is the YLLs expected at baseline, RR_{B}^{i} is the RR of condition i due to the physical activity at baseline, RR_C^i is the RR of condition *i* due to both the baseline activity and the additional cycling, $METS_B$ is the MET hours of PA at baseline, $RR_{Ref}{}^i$ and $METS_{Ref}{}^i$ are the sampled reference RR and reference MET hours associated with disease *i* in the systematic review of Woodcock et al. (2009), $METS_C$ is the additional MET hours of cycling and λ^i is the power transformation of the exposure. The change in the expected YLDs was calculated in the same way.

2.4. Health impacts of external pollution exposure

The marginal external air pollution health impact of a single additional cyclist was found by estimating in parallel, the societal air pollution health impacts in the CS and RS as shown in Fig. 2. It was assumed that a reduction in the vehicle km travelled in Dublin would lead to a proportional reduction in $PM_{2\cdot5}$ emissions attributable to vehicular transport. It was also assumed that the change in ambient $PM_{2\cdot5}$ concentration would be proportional to the change in the total $PM_{2\cdot5}$ emissions. According to the Central Statistics Office of Ireland (Central Statistics Office, 2012) transport accounted for 31% of $PM_{2\cdot5}$ emissions in Ireland in 2010. In order to estimate the percentage reduction in motorised transport it was necessary to estimate the total baseline km travelled including non-commute trips. This was estimated from the NTA travel survey of 2012 (National Transport Authority, 2013). For each RS and CS, the change in $PM_{2\cdot5}$ concentration was estimated. The changes in risk of respiratory diseases, cardiovascular diseases and lung cancer in the population of Dublin for the RS and CS were then estimated using health impact models based on the APHEIS study (Medina et al., 2009). Similarly to the physical activity models, for each health condition and iteration, a reference relative risk (RR) was sampled from a lognormal distribution with mean and 95% CI equal to the mean and CI found in APHEIS study. The age and gender structure of the population of Dublin was available from the CSO (Central Statistics Office, 2014) and the baseline YLDs and YLLs rates for each age group and gender were available from the WHO (World Health Organisation, 2013). The change in YLLs for each condition, *i*, in each age and gender group could then be calculated using Eqs. (4) and (5).

$$\Delta YLL^{i,p} = N_p * YLL_B{}^{i,p}(1 - RR_C{}^i) \tag{4}$$

$$RR_C{}^i = RR^i_{Ref}\,\Delta C/\Delta C_{Ref} \tag{5}$$

Where $\Delta YLL^{i,p}$ is the change in expected YLLs lost due to condition, *i*, by the exposed age/gender group *p*, N_p is the number of individuals in the age/gender group *p*, $YLL_B{}^{i,p}$ is the baseline expected YLLs associated with condition *i* and group *p*, RR^i_{Ref} is the sampled reference RR for condition *i*, ΔC_{Ref} is the reference concentration change for condition *i* and ΔC is the change is concentration of $PM_{2\cdot5}$ in μg/m^3. The marginal change in external air pollution YLLs was calculated by finding the difference between the changes in YLLs in the RS and the CS.

2.5. Health impacts of individual pollution exposure

Pedestrians and cyclists are exposed to higher intake doses of toxic pollutants than users of other modes, mainly due to their elevated ventilation rates (Nyhan et al., 2014). To estimate the impact of the increased inhaled dose of the test subject switching from private car travel in the RS to cycling in the CS, first the ratio of the subject's yearly inhaled dose of $PM_{2\cdot5}$ between the two scenarios was estimated using the same method as Doorley et al. (2015a), assuming 221 commuting days per year. It was assumed that the health impact of the increase in inhaled dose would be equivalent to the impact of an increase in average ambient $PM_{2\cdot5}$ concentration which would lead the same increase in inhaled dose. As with the external health impacts of air pollution, the RRs of cardiovascular diseases, respiratory diseases and lung cancer were calculated for the test subject in the CS and in the RS based on the reference RRs of the APHEIS study. The baseline expected YLLs and YLDs of the test subject for a given year were assumed to be equal to the per capita YLL and YLD rates of the same age and gender group in Ireland in 2012. The individual's change in expected yearly YLLs due to the conditions could be estimated for the CS and RS using Eqs. 6 and 5.

$$\Delta YLL^i = YLL_B{}^i(1 - RR_C{}^i) \tag{6}$$

Where ΔYLL^i is the change in the individual's expected YLLs due to condition *i*, $YLL_B{}^i$ is the individual's baseline expected YLLs due to condition *i*, RR^i_{Ref} is the sampled reference RR for condition *i*, ΔC_{Ref} is the reference concentration change for condition *i* and ΔC_{eq} is the equivalent change in concentration of $PM_{2\cdot5}$. Since cardiovascular disease risk is influenced by both physical activity and pollution exposure, the impacts of the two exposures were modelled multiplicatively. The expected change in individual air pollution YLLs was calculated by finding the difference between the changes in air pollution DALYs in the RS and the CS.

2.6. Individual traffic collisions

In both the RS and the CS, the per-km risks for each mode of being a victim of a fatal, serious or minor collision were estimated using a model similar to that used by Woodcock et al. (2013). This model assumes that the number of traffic collisions between each pairwise combination of modes is non-linearly related to the total distance travelled by each mode in the network. The degree of non-linearity of the relationship between distance travelled and number of collisions is unclear and likely to vary between different transport environments. Therefore, in the current study, instead of using the constants of non-linearity suggested by Woodcock et al. (2013), each constant in each iteration was sampled from a normal distribution with a mean of the value suggested by Woodcock et al. (2013) and coefficient of variation of 0·5.The baseline collision data used in the model were obtained from the Road Collision

Table 1
Fatality and Injury risk factors by age and gender.

Gender	Age Group	Driver		Cyclist	
		Fatality Factor	Injury Factor	Fatality Factor	Injury Factor
Male	20–24	2.6	1.8	0.7	0.8
Male	25–29	2.6	1.8	0.7	0.8
Male	30–34	0.9	0.8	0.9	0.7
Male	35–39	0.9	0.8	0.9	0.7
Male	40–44	0.5	0.5	0.5	0.5
Male	45–49	0.5	0.5	0.5	0.5
Male	50–54	0.5	0.5	1.4	0.7
Male	55–59	0.5	0.5	1.4	0.7
Male	60–64	0.5	0.5	1.7	0.8
Female	20–24	0.9	1.4	0.4	0.6
Female	25–29	0.9	1.4	0.4	0.6
Female	30–34	0.3	0.8	0.7	0.6
Female	35–39	0.3	0.8	0.7	0.6
Female	40–44	0.3	0.5	0.7	0.6
Female	45–49	0.3	0.5	0.7	0.6
Female	50–54	0.4	0.6	0.8	0.9
Female	55–59	0.4	0.6	0.8	0.9
Female	60–64	0.7	0.8	1.0	1.4

Handbook, 2011 and 2012 (Road Safety Authority, 2011, 2012) and corrected for underreporting using the correction factors provided by the HEATCO study (Bickel et al., 2006). The baseline distances travelled by each mode were estimated using the same method as Doorley et al. (2015a).

The modal per-km risks calculated in this way were generic values for all users of the mode in that scenario. However, it is well documented that age and gender have a significant impact on the likelihood of an individual using a particular mode being involved in a traffic collision (Short and Caulfield, 2014; Woodcock et al., 2014). Mindell et al. (2012) have estimated the risk of fatality and hospitalisation for different age groups and genders per km travelled by driving and by cycling in England. For the current study, these results were used to estimate scaling factors for each age/gender group representing the ratio of their risk of fatality or injury to the risk of fatality or injury for the general population. The estimated scaling factors are shown in Table 1. These factors were used to correct the per-km risks from the traffic collision model, based on the age and gender of the test subject. The expected numbers of each type of collision for the test subject were then calculated for the RS and CS by multiplying the appropriate modal per-km risk by the kms travelled annually. The change in collision risk for the test subject due to the switch to cycling could then be calculated by comparing the expected numbers of each type of injury between the CS and RS.

In order to convert the change in expected incidence of injuries to a change in expected DALYs, the lost YLLs and YLDs associated with each type of injury needed to be estimated. For fatal injuries, the YLLs lost were assumed to be equal to the remaining life expectancy of the test subject. The average remaining life expectancy for an individual in each five-year age and gender group was obtained from the CSO (CSO, 2015). 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 (Tainio et al., 2014) 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.

2.7. External traffic collisions

The traffic collision model of (Woodcock et al., 2013) was also used to estimate the change in injury risk for other users of the network as a result of the test subject switching from driving to cycling. The km travelled by each mode excluding the test subject was constant between the CS and RS but the per-km risk of each type of injury was not. For both the CS and RS, the external injuries of each severity level in each mode were found multiplying the per-km injury risk by the km travelled by that mode excluding the test subject. The change in external traffic injuries could be calculated by taking the difference between the external injuries in the CS and RS. The lost YLLs associated with an external traffic fatality were found by calculating the average remaining life expectancy among the 20–64 age group in the population of Dublin. The YLDs associated with serious and minor injuries were the same as those used for injuries to the individual cyclist.

Table 2
Current and Potential Cycling in Dublin.

Gender	Age Group	Current Cyclists		Potential Cyclists	
		N	Average journey distance (km)	N	Average journey distance (km)
M	20 to 24	880	5·62	1737	3·67
M	25 to 29	2888	5·44	4171	3·77
M	30 to 34	3505	6·07	5053	3·76
M	35 to 39	2878	6·44	4097	3·79
M	40 to 44	2192	6·69	3711	3·78
M	45 to 49	1712	6·74	3671	3·81
M	50 to 54	1390	6·99	3210	3·84
M	55 to 59	893	6·62	2449	3·84
M	60 to 64	465	6·50	1584	3·82
F	20 to 24	349	5·48	2522	3·68
F	25 to 29	1415	5·36	5872	3·73
F	30 to 34	1583	5·78	5899	3·76
F	35 to 39	1011	5·89	4818	3·73
F	40 to 44	735	6·45	4472	3·68
F	45 to 49	613	6·21	4766	3·63
F	50 to 54	514	6·24	3991	3·68
F	55 to 59	273	6·07	2885	3·72
F	60 to 64	141	5·73	1626	3·75

3. Results and discussion

The mean journey-to-work distances of the current and potential cyclists in County Dublin are shown in Table 2. For each of the MS scenarios defined in the Methods section, the mean estimated impacts on YLDs and YLLs are shown for each health condition in Table 3. Negative values indicate loss of YLLs or YLDs. For the health impacts to the individual cyclist, the changes in YLDs and YLLs are also expressed as percentages of the individual's baseline expected YLDs and YLLs for each health condition. The most significant positive benefit for all MSs was due to a reduction in YLLs due to cardiovascular disease. Other significant impacts related to PA include a reduction in YLDs due to depression and diabetes and a reduction in YLLs due to breast cancer and colon cancer. On average, the test subject's expected YLLs and YLDs due to traffic collisions increased by factors of 23 and 15 when they switched from

Table 3
Mean YLLs and YLDs saved per year due to uptake of cycling by individual commuters. Positive values indicate health benefits.

		Current		Intermediate		Smarter	
		Mean Change	Mean % Change	Mean Change	Mean % Change	Mean Change	Mean % Change
Individual Physical Activity							
Breast Cancer	10^{-3} YLDs	0.03	9.18	0.03	10.71	0.03	10.75
	10^{-3} YLLs	0.35	9.18	0.36	10.71	0.35	10.75
Colon Cancer	10^{-3} YLDs	0.01	10.70	0.01	19.20	0.01	19.22
	10^{-3} YLLs	0.33	10.70	0.33	19.20	0.33	19.22
Cardiovascular Diseases	10^{-3} YLDs	**0.61**	19.18	**0.62**	18.16	**0.62**	18.13
	10^{-3} YLLs	**2.59**	19.18	**2.60**	18.16	**2.61**	18.13
Dementia	10^{-3} YLDs	0.13	18.17	0.13	17.00	0.13	17.00
	10^{-3} YLLs	0.03	18.17	0.03	17.00	0.03	17.00
Depression	10^{-3} YLDs	**2.30**	17.00	**2.30**	15.88	**2.29**	15.86
	10^{-3} YLLs	0.00	17.00	0.00	15.88	0.00	15.86
Diabetes	10^{-3} YLDs	**0.51**	15.86	**0.51**	0.00	**0.51**	0.00
	10^{-3} YLLs	0.12	15.86	0.12	0.45	0.12	0.45
Individual Pollution Exposure							
Respiratory Diseases	10^{-3} YLLs	−0.01	−0.45	−0.01	−0.45	−0.01	−0.45
Cardiovascular Diseases	10^{-3} YLLs	−0.07	−0.68	−0.07	−0.68	−0.07	−0.68
Lung Cancer	10^{-3} YLLs	−0.04	−0.00	−0.04	−0.00	−0.04	−0.00
External Pollution Exposure							
Respiratory Diseases	10^{-3} YLLs	0.08	[a]	0.08	[a]	0.08	[a]
Cardiovascular Diseases	10^{-3} YLLs	0.41	[a]	0.41	[a]	0.41	[a]
Lung Cancer	10^{-3} YLLs	0.17	[a]	0.17	[a]	0.17	[a]
Individual Collision Risk	10^{-3} YLDs	**−1.99**	**−1506.47**	**−1.82**	**−1375.93**	**−1.68**	**−1272.28**
	10^{-3} YLLs	**−0.73**	**−2214.64**	**−0.68**	**−2075.14**	**−0.65**	**−1971.48**
External Collision Risk	10^{-3} YLDs	**1.49**	[a]	**1.33**	[a]	**1.21**	[a]
	10^{-3} YLLs	0.37	[a]	0.33	[a]	0.29	[a]

[a] Percentage changes for external impacts are not informative so they are omitted.

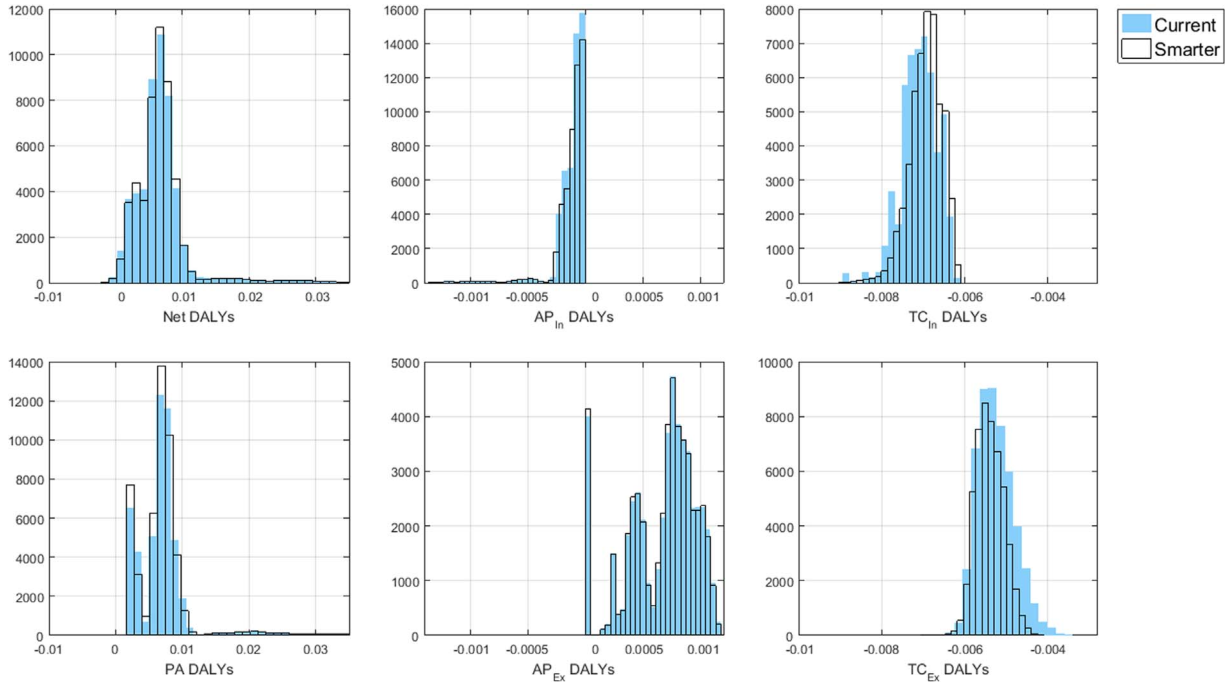

Fig. 3. Distributions of health impacts in the Current and Smarter Travel MS.

private car to cycling in the Current MS but these factors decreased slightly in the Intermediate and Smarter Travel MS. These factors are higher than the typical ratio of cycling injury risk to driving injury risk (Elvik, 2009) and this difference can be attributed to the incorporation of underreporting and demographic risk factors in this study. As a result of these large increases in collision risk, there was a negative mean impact on TC DALYs for the cyclists themselves in each MS. However, a single driver switching to cycling in any MS had a positive mean impact on TC DALYs for the rest of the network. There was little difference in the AP_{Ex} estimates between the Current, Intermediate and Smarter Travel MSs but this is to be expected as the marginal external pollution costs of transport tend to be similar to the average external pollution costs (Korzhenevych et al., 2014). Further insights can be gained by examining not just the mean values but the distributions of total DALYs saved across all subjects tested. The distributions are shown for the Current MS and the Smarter Travel MS in Fig. 3.

The histograms of all of the impacts look similar between the Current and Smarter Travel MS. In each case, the PA health impact is the most significant impact and is non-negative. The histograms of the AP_{In} impact and the AP_{Ex} impact respectively are entirely negative and entirely positive in both the Current and Smarter MS. Overall, the AP_{In} and AP_{Ex} impacts are not significant when compared to the other impacts. The histogram of the TC_{In} impact was entirely negative whereas the TC_{Ex} impact estimates are almost entirely positive. The distribution of TC_{In} impacts shifted positively in the Smarter MS relative to the Current MS while the distribution of TC_{Ex} impacts is shifted negatively. These were the only impacts which showed an obvious difference due to the change in background modal split.

3.1. Net individual and external impacts

The histogram of Net DALYs shows that the total expected public health impact of the switch from driving to cycling was positive in almost all cases. In both the Current and Smarter Travel MS the total expected health impact was negative in less than 1% of cases. By grouping the impacts into individual and marginal external impacts, we can see more clearly how both the individual new cyclists and the rest of society were affected. Fig. 4 shows the net impact to individuals due to the sum of the PA, AP_{In} and TC_{In} impacts and the net marginal external impact due to the sum of the AP_{Ex} and TC_{Ex} impacts. When the net individual DALYs are considered in isolation, negative impacts are expected in a higher proportion of cases than when total Net DALYs were considered —8% and 6% in the Current and Smarter Travel MS respectively. This means that, within the bounds of the model uncertainties considered in this study, cycling may have a negative net health impact for individuals of certain broad characteristics. The overall distribution of individual DALYs is bimodal and, as discussed in the next section, this is due to the difference in expected health impacts experienced by the youngest age groups and the rest of the subjects. The net marginal impact to society, however, was almost always positive and was generally higher in the Current MS than the Smarter Travel MS, as shown in Fig. 4. These observations show that, in some cases, if individual and external impacts are considered in aggregation, a negative expected impact to the individual may be masked by a positive expected external impact.

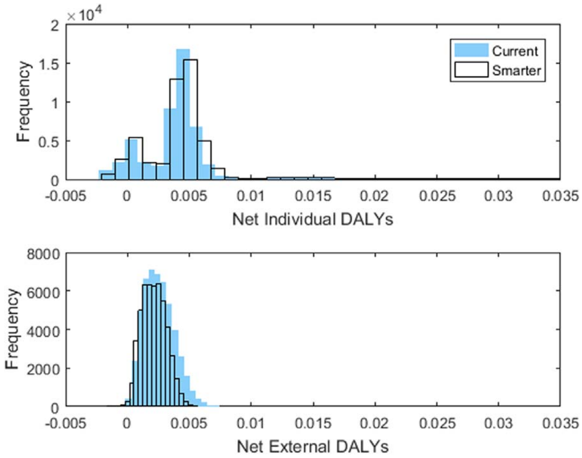

Fig. 4. Net individual health impacts and net marginal external health impacts in the Current and Smarter Travel MS.

3.2. Effects of age and gender

The specific cases in which negative individual health impacts may be expected were found to be closely related to age and gender. This is illustrated by Figs. 5 and 6 which show the distributions of Net individual DALYs and their two most significant components, PA DALYs and TC $DALYs_{In}$ in each age and gender group. Only the Current MS results are shown but the results in the other MS stages were similar. In both genders, the DALYs saved due to PA were lowest for the 20–29 age groups and highest for the 60–64 age group. This is because the lowest age groups have a relatively low baseline risk of the health conditions considered, whereas the higher age groups have higher baseline disease risks. The increase in collision risk was also relatively significant for the highest age groups. However, the over 60 age group experienced the greatest net health benefits as this relatively high increase in injury risk seems to have been outweighed by their large reduction in disease risk. The 20–29 age groups were the only groups where some individuals experienced negative net heath impacts as the health benefits they gained from physical activity were not enough to counteract their increase in collision risk. This observation that the benefits of cycling may not outweigh the harms in the case of young people is in agreement with another recent study which also considered age-specific health effects (Woodcock et al., 2014). The effect of gender is most clear for the youngest and oldest age groups. Older males experienced greater positive health impacts than older females due to their higher baseline DALY rates but younger males also experienced greater negative health impacts than younger females due to their increased risk of traffic injuries.

The individual net health benefits were also correlated with distance travelled. Figs. 7 and 8 show that, for ages 20–29, net individual DALYs were negatively correlated with distance and net negative impacts only occurred for longer trips. This can be explained by observing that individual collision risk increases linearly with distance travelled while the health benefits of physical

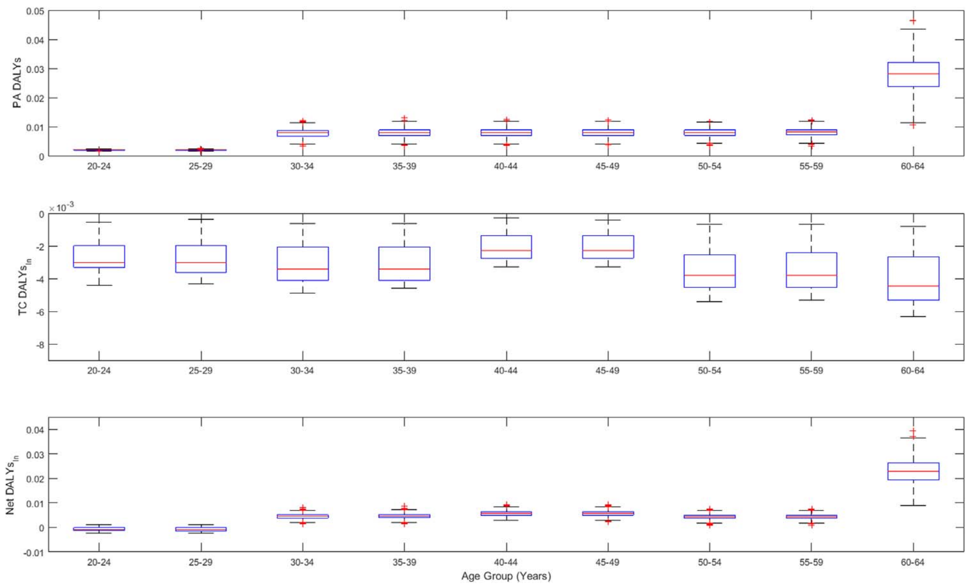

Fig. 5. DALYs saved by male test subjects disaggregated by age.

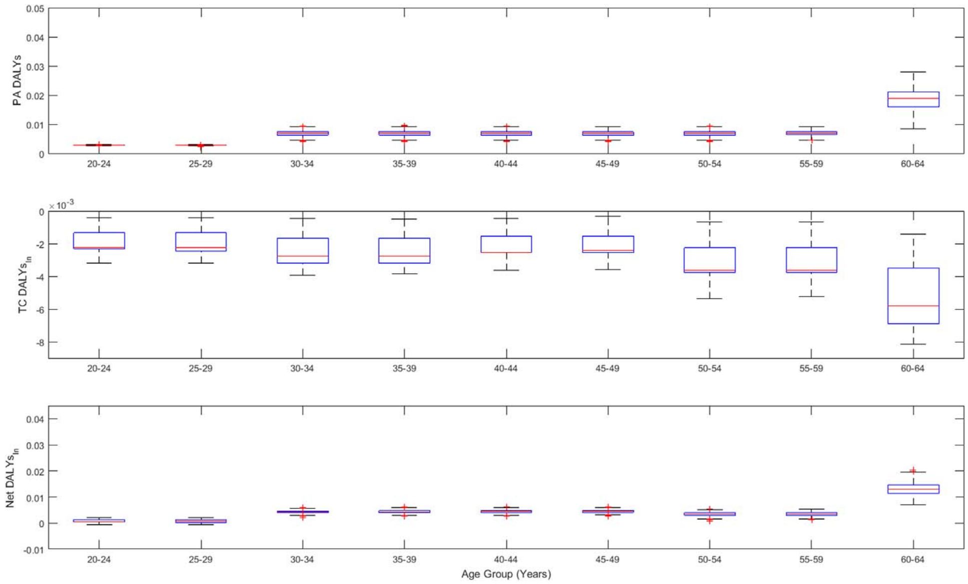

Fig. 6. DALYs saved by female test subjects disaggregated by age.

activity increase log-linearly. Effectively, this means that a large part of the health benefits of cycling can be attained with a small amount of cycling per week and after this the physical activity benefits increase more slowly while the traffic collision risk continues to increase linearly. Above the age of 29, net individual DALYs were not strongly correlated with commute distance as collision risk becomes less significant.

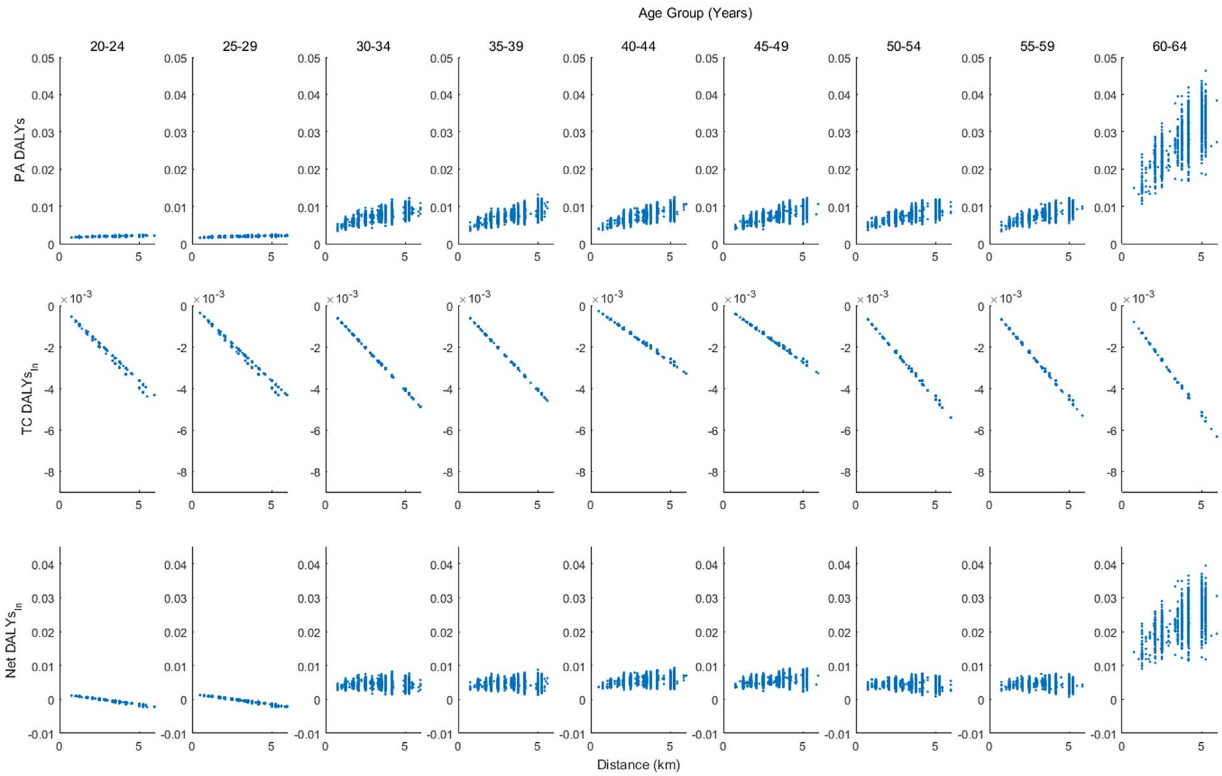

Fig. 7. Relationship between DALYs saved and commute distance for male test subjects disaggregated by age.

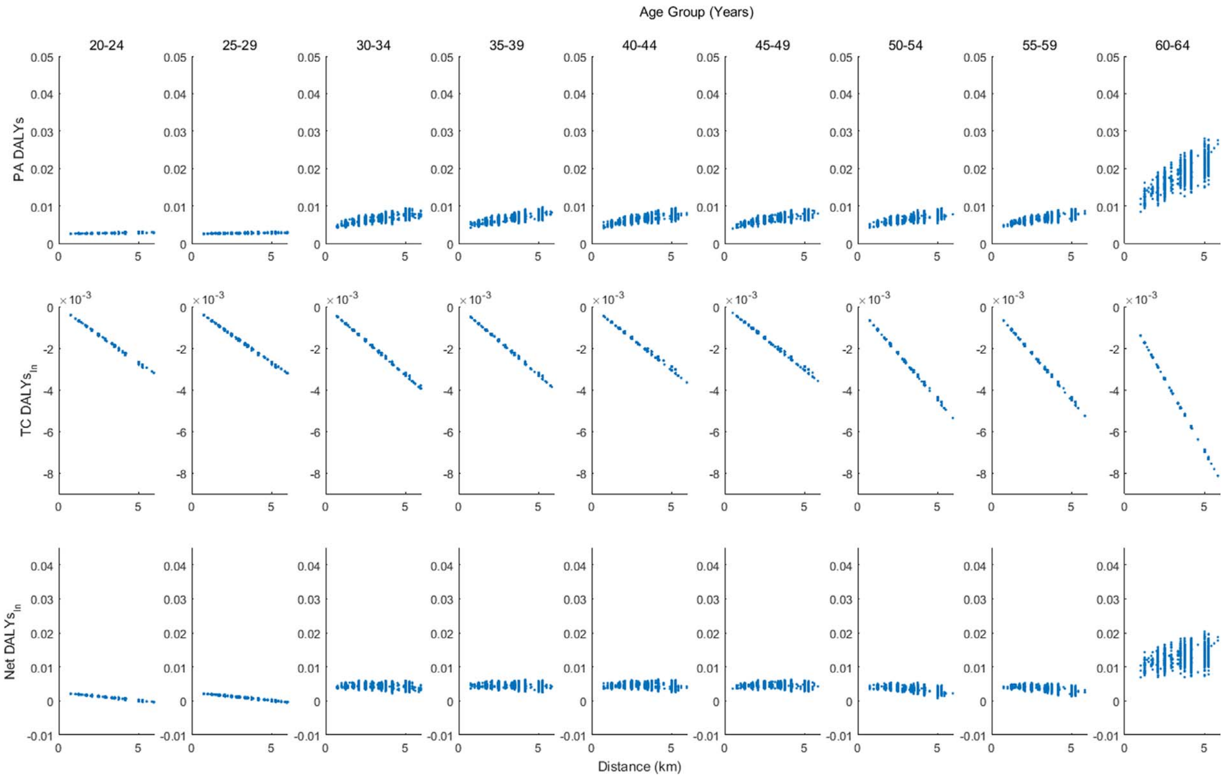

Fig. 8. Relationship between DALYs saved and commute distance for female test subjects disaggregated by age.

3.3. Effect of Modal Split

While net individual health impacts did not appear to depend strongly on the MS, the net external health impacts shifted negatively in the Smarter MS. The difference in the distribution of marginal external impacts between the Current and Smarter MS was mainly due to the difference in the distribution of TC_{In} and TC_{Ex}. The change in the TC_{In} and TC_{Ex} impacts between the MS stages can be seen more clearly in Table 4 which shows the mean of each impact in the Current, Intermediate and Smarter Travel MS. As the modal split changes in favour of more cycling and less private car use, the mean TC_{In} moves positively while the mean of TC_{Ex} moves negatively. This shows that as cycling increases, the negative impact on collision risk of the individual is mitigated by the "Safety in Numbers" effect (Elvik, 2009). However, the positive impact on collision risk for the rest of the users of the transport network is also slightly reduced. This indicates that in terms of improving the safety of the rest of the network, the marginal returns from replacing private cars with bicyclists diminish with increasing modal share of cycling.

3.4. Strengths and weaknesses

This study was based on highly reliable individualised census data for the study area and included age and gender specific effects and, as such, the results are more specific than studies based on population level data. However, for certain parameters such as the constants of non-linearity in the collision model, no local estimates were available so estimates from other studies which were not location-specific were used. The use of local data where possible increases the reliability of the findings of this study but also may make it more difficult to generalise these findings to other study areas.

The method used to design the scenarios in order to estimate individual and marginal health impacts is a novel approach which allowed a unique perspective on the impacts of increments in cycling. However, although the underlying models were derived from strong epidemiological evidence, it should be noted that the results of modelling studies have lower reliability than observational or

Table 4
Mean change in Traffic Collision DALYs in each modal split stage.

Modal Split	Mean Individual TC DALYs	Mean External TC DALYs
Current	−2.73E-03	1.86E-03
Intermediate	−2.50E-03	1.66E-03
Smarter	−2.33E-03	1.50E-03

experimental studies. This is especially true when dealing with a very complex system such as a transport network which requires many assumptions to be made. Cohort studies or randomised controlled trials are costly and difficult to implement for a major lifestyle choice such as cycling to work, which can be expected to be highly correlated with many other lifestyle factors. In the absence of such empirical evidence, modelling studies such as this one can be useful for policy formulation.

The use of the models provided by Woodcock et al. (2009) and Boldo et al. (2006) allowed the health impacts to be broken down by individual health conditions, giving more specific insights than results based on mortality alone. Since there may be other conditions not included in these models which are relevant to cycling, it is possible that the PA and/or AP impacts are underestimates. However, it is unlikely that other health conditions would have comparable impacts at the low levels of cycling being considered in this study (Woodcock et al., 2014). It should also be noted that this study only considered the health impacts of cycling and that increased levels of cycling are generally accompanied by other societal benefits such as reductions in CO2 and congestion. However, such considerations would not affect the impacts to the individual cyclists.

3.5. Implications and future work

There are important policy implications of the finding that the benefits of cycling are unevenly distributed. Firstly, economic incentives for commuter cyclists such as Ireland's Bike to Work scheme are justified since society gains from additional commuters switching to cycling whereas, in some cases, the new cyclists themselves may not. Secondly, it should be noted that the only significant negative health impact for the individuals who switch to cycling is due to the large increase in traffic collision risk. This suggests that in order to ensure that the net health impacts of switching from driving to cycling are positive, the risk of traffic collisions for cyclists in the Dublin network must be reduced through provision of adequate infrastructure and improving driver awareness and perception of cyclists. As this study was focussed on behavioural change, it was assumed that in the scenarios involving increased cycling, the infrastructure remained the same. However, if improvements in infrastructure lead to increased cycling or vice versa, the impact of increases in cycling on traffic collisions are likely to be more positive. Studies which incorporate this possible correlation would provide further useful information for both the health and transportation sectors. The histogram of individual net impacts in the Smarter Travel modal shift was shifted slightly positively in comparison to the Current Modal shift implying that in a less motorised transport network, the benefits experienced by an individual who begins cycling would be higher. It is likely that the reverse would also be true and that the net health impact experienced by someone who begins cycling in a highly congested city would be less positive. This should be considered by policy makers considering measures to promote cycling in highly congested cities. Finally, the observation that younger individuals benefit less from switching to cycling than older individuals suggests that efforts to promote cycling should be aimed towards the 30+ age group while efforts to encourage cycling safety and adherence to the rules of the road should be aimed at younger cyclists.

4. Conclusions

This study has built on recent research into the health benefits of cycling by making a clear distinction between benefits to individual cyclists and the surrounding population. A novel simulation approach utilized the 2011 census data for Ireland and found that health impacts to the surrounding population of a single additional commuter switching to cycling would range from 0 to 0.006 DALYs/year. The health impacts to individuals switching from driving to cycling would range from −0.003 to 0.033 DALYs/year. Negative expected health impacts were found only for some individuals in the 20–29 age group. If the health impacts had been considered at an aggregate level, these negative individual health impacts would have been masked. This underscores the importance of distinguishing between individual and external health impacts and considering age-specific effects when evaluating the health impacts of cycling. In light of the positive impacts for the local population and for the majority of cyclists, it remains important to promote cycling as an alternative to driving, particularly for short trips. However, promotion of cycling should be accompanied by measures to mitigate risks to the cyclists themselves to ensure that the overall health benefits do not come at the expense of a small group of cyclists. Since traffic collisions are the only significant health risk to cyclists, measures such as traffic calming in residential areas and segregated facilities in urban areas are of particular importance.

Conflict of interest

There is no conflict of interest among the authors.

Acknowledgements

This research was supported by the Environmental Protection Agency of Ireland (Project number: 2012-EH-PhD-11).

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