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Using floating bike data to determine cyclist exposure to poor air quality

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A B S T R A C T

Introduction: The World Health Organisation (WHO) claims that 9 out of 10 people breath air containing high levels of pollutants, while air pollution itself is responsible for around 7 million premature deaths every year (WHO, 2014). This paper aims to determine the health impacts of such air pollutants on the cyclist population of Dublin City through the use of floating bike data and emission modelling software.
Methods: Through the use of COPERT Street Level vehicle emissions are estimated and Operational Street Pollution Model, NO_2 and $PM_{2.5}$ quantities and NO_2 concentrations were modelled on four separate roads that had been identified as some of the busiest cycle corridors in Dublin city through the use of floating bike data. The NO_2 quantities were then used to estimate the associated economic impact and concentrations were used to estimate the health impact on the exposed cyclist population using the WHO Burden of Disease (BOD) method.
Results: The results suggested that as much as 18.4 million Euro worth of damage is done each year on just one of the four roads modelled in this research, indicating that the total damage being done in Dublin city could reach into the billions a year, as this is only considering NO_2 pollution on one road. In terms of the BOD results, it was calculated that as many as 37 premature deaths could be caused due to exposure to the NO_2 concentrations modelled, resulting in 412 Years of Life Lost (YLL).
Conclusions: Through the use of modelled scenarios where the fleet configuration changes, the findings of this study create an argument that significant measures need to be taken to reduce the air pollution levels in Dublin in order to prevent the needless infliction of disease and premature death on the relevant exposed population.

1. Introduction

In Dublin, 42% of all trips are made by car and 9% of trips are taken by bicycle (NTA, 2017). One of the most notable change in travel patterns in the past decade has been the sharp rise in the number of people who cycle to work, rising by nearly 43% (Central Statistics Office, 2016a). This increase in cyclists is seeing a return to the kind of numbers seen in the 1980's, when the private car really began to dominate in mode choice. The reason for this increase in recent years could be partly attributed to the economic downturn, as people opted for cheaper modes of transport to cut costs and since then it has been boosted by the introduction of many different schemes and programmes to incentivise people to cycle (Caulfield, 2014). The first scheme of note was Dublin Bikes which was introduced to Dublin city centre in 2009, with it being very successful since its launch, making over 30 million journeys in early 2020 (Dublin City Council, 2020). In 2016, Ireland's first station-less bike sharing scheme was launch called Bleeperbike. While this scheme is smaller than the Dublin Bike scheme however, because it's a station less scheme it allows for greater coverage to parts of the city that are not serviced by Dublin Bikes.

Road transport is responsible for the emissions of various regulated and unregulated pollutants (Gkatzoflias et al., 2006). The transport sector was responsible for 19.5% of Ireland's total Greenhouse Gases emissions in 2014, and this proportion is expected to

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increase significantly beyond 2020 (Environmental Protection Agency, 2016). The Environmental Protection agency uses COPERT to estimate emissions from road transport in Ireland. COPERT is a software programme aimed at calculating air pollution from road transport and is the current EU standard vehicle emissions *calculator*. It uses a variety of vehicular data inputs including fleet size and composition, yearly mileage, average speed and other environmental data such as air temperature and humidity to calculate emissions and energy consumption for a specific country or region. COPERT is partially used in this study to estimate the emission levels of harmful pollutants such as $PM_{2.5}$ and NO_2 in Dublin City by using the traffic flow in Dublin city.

Air pollution is responsible for around 7 million premature deaths worldwide (WHO, 2014). The WHO have published many documents illustrating the health effects that air pollution can cause that can ultimately lead to premature death and how to calculate this. By reducing air pollution levels, countries can reduce the burden of disease from stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma (WHO, 2018). These publications are used in this study in conjunction with the emission estimates, calculated using modelling programmes, to estimate the health impact of emissions in Dublin city on the cyclist population.

As well as examining the current state of emissions in Dublin city, several scenarios are also be modelled in this study where the fleet of vehicles on the roads is altered to observe the changes in emission levels. These scenarios provide insight into how the harmful pollutants can be reduced to alleviate the health impacts on the exposed population and ultimately reduce the number of premature deaths in Ireland. Our paper uses two approaches, it firstly estimates the reductions in emissions in the study and the damage costs are also estimated. Secondly, the ambient air pollution concentrations are modelled to estimate the impacts levels of $PM_{2.5}$ and NO_2 have upon cyclists health.

2. Literature review

2.1. Emissions recording and reporting

Transportation is one of the largest sources of both greenhouse gas and non-greenhouse gas emissions in the EU. In Ireland, 20.3% (11.6 Mt CO_2-eq) of all greenhouse gas emissions were produced by the transport sector (Environmental Protection Agency, 2020). The literature indicates that a large portion of these emissions are produced by road transport in particular. Road transport is responsible for the emissions of various regulated and unregulated pollutants (Gkatzoflias et al., 2006). The main pollutants discharged from road transport are CO_2, CO, NO_2, $PM_{2.5}$, PM_{10}, VOC, NMVOC (European Environment Agency, 2017). While greenhouse gases such as CO_2 are responsible for global warming and climate change, non-greenhouse gases like CO, NO_2, VOC, NMVOC and the PMs directly or indirectly affect human health.

Although there are many different emission modelling software programmes in use all over the world, there are two programmes widely used in Europe. These two programmes are HandBook Emission FActors for road transport (HBEFA) and COmputer Programme to calculate Emissions from Road Transport (COPERT). Although some European countries have developed their own model to use, HBEFA and COPERT dominates the European countries. As this research project is focussed on emission modelling in Ireland, COPERT was used, it is obvious that both of these programmes should be considered.

COPERT is an (Irish) EPA approved software tool that has been designed to develop National or state level motor vehicle emission inventories (MVEIs), and Emission factors as a function of vehicle speed for road based emission calculations (Carroll et al., 2016). COPERT is the EU standard vehicle emission calculator recommended by the European Environment Agency and over 20 countries in Europe use (EMISIA, 2020). COPERT v5.2 is the latest available version available currently (EMISIA, 2019).

2.2. Health effects of emissions

The WHO (2014) reported that in 2012, around 7 million people died globally – one in eight of total global deaths - as a result of air pollution exposure. This finding more than doubles previous estimates and confirms that air pollution is now the world's largest single environmental health risk. In Europe in particular, 518,700 premature deaths were attributable to $PM_{2.5}$, NO_2 and O_3 exposure in 41 countries (European Environment Agency, 2018). Air pollution has also been associated with several health effects including stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma (WHO, 2018).

The health impacts of air pollution are generally quantified in terms of premature deaths (mortality) and morbidity. In this case, mortality represents a reduction in life expectancy due to premature deaths as a result of air pollution exposure, whereas morbidity represents the level of health and wellbeing of a person as a result of air pollution exposure. Premature deaths are deaths that occur before a person reaches their relative expected age. This expected age is usually the age of standard life expectancy for a country stratified by sex. Premature deaths are considered to be preventable if their cause can be eliminated (European Environment Agency, 2018). Whereas, morbidity relates to the occurrence of illness and years lived with disability or disease. Morbidity includes not only chronic or debilitating conditions, but also less severe health effects because air pollution affects the population on a daily basis and may lead to a worse overall health condition. Morbidity outcomes include hospitalisation and emergency room visits, asthma attacks, bronchitis, respiratory symptoms, and lost work or school days (Dey, 2018). These impacts are referred to as Burden of Disease (BOD) of air pollution and are usually measured in terms of Disability-Adjusted Life Years (DALY), which is the sum of the Years of Life Lost (YLLs) due to premature death and the Years Lived with Disability (YLDs) (WHO, 2003). YLLs are defined as the years of potential life lost due to premature death. It is an estimate of the average number of years that a person would have lived if they had not died prematurely (European Environment Agency, 2018). YLL is lower for deaths at an older age and greater for deaths at a younger age as it considers the age of death. Therefore, expressing premature deaths in terms of YLL gives more precise information than simply stating the number of premature deaths alone. Similarly, expressing morbidity rates in terms of YLD gives more precise information than simply stating the number of incidents where diseases were caused by air pollution.

One of the most popular approaches to quantifying these terms is by using RR (Relative Risk) coefficients. These coefficients represent the health impact of a unit change in air pollutant concentrations. RR coefficients are derived from concentration-response functions which represent the relationship between exposure to pollution as a cause and specific outcomes as an effect (WHO, 2004). Methods of air pollution health risk assessment have been well established in Europe since the first European project and have been adopted in many global projects including the first global burden of disease study (Héroux et al., 2015). There are air quality guidelines designed by WHO which aim to reduce health impacts of air pollution that are periodically updated in line with new research (WHO, 2005). These air quality guidelines are developed based on extensive scientific evidence on air pollution and associated health consequences. However, though these guidelines offer reduced health impacts, the concentrations below these guideline values are found to possess health threats. A study carried out by Raaschou-Nielsen et al. (2012) found that a change of 10 μg/m^3 in NO_2 concentrations in air pollution showed a significant correlation with health outcomes in Denmark. Clancy et al. (2002) examined the effect of air pollution control measures on death rates in Dublin and reported that control of particulate air pollution causes significant reductions in respiratory and cardiovascular deaths, which shows that further air pollution control could substantially diminish daily death in Dublin.

Particulate Matter is a mixture of aerosol particles (solid and liquid) covering a wide range of sizes and chemical compositions. PM_{10} refers to particles with a diameter of 10 μm or less and $PM_{2.5}$ refers to particles with a diameter of 2.5 μm or less. Therefore, PM_{10} includes all of $PM_{2.5}$. PM is either directly emitted as primary particles or it forms in the atmosphere from emissions of SO2, NO_2, NH3 and NMVOCs. PM is emitted from many anthropogenic sources, including both combustion and non-combustion sources. Important natural sources of PM are sea salt and natural re-suspended dust. PM can cause or aggravate cardiovascular and lung diseases, heart attacks and arrhythmias. It can also affect the central nervous system and reproductive system, and cause cancer. One outcome of exposure to PM can be premature death (European Environment Agency, 2014). In 2018, it is estimated that $PM_{2.5}$ alone was the cause of 422,000 premature deaths (European Environment Agency, 2018). Boldo et al. (2006) found that 16,926 premature deaths as a result of long-term exposure to $PM_{2.5}$ could be prevented every year if the $PM_{2.5}$ levels were reduced to 15 μg/m^3 in each of the 23 cities included in the study. Equivalently, this would increase life expectancy at age 30 by a range between one month and more than two years in the cities studied (Boldo et al., 2006). Several other studies (Fann et al., 2018; Martinez et al., 2018; Song et al., 2017; Yin et al., 2017) were carried out to estimate the health impacts of $PM_{2.5}$. It is clear from the number of studies carried out on the health effects of PM on the exposed population and their consistent results that PM can be extremely harmful to human health in terms of both premature death and morbidity rates.

Similar to PM, exposure to NO_2 has been linked with a range of serious health effect, including asthma and other respiratory diseases (United States Environmental Protection Agency, 2019). NO_2 has been found to be responsible for 79,000 premature deaths in 2018 (European Environment Agency, 2018). In urban areas such as cities, road traffic is a major contributor to NO_2 concentration levels. In a study carried out by Tao et al. (2012), it was found that exposure to an increased level of NO_2 concentration by 10 μg/m3 over 2 days resulted in a rise in mortality rates by 1.95% at 95% confidence interval. A study looking at NO_2 concentrations in Athens, Greece and their subsequent health implications showed that people suffering from respiratory disease are very sensitive to NO_2 at high concentrations (Chaloulakou et al., 2008). This same study also suggests that if NO_2 concentrations were reduced to the levels of the annual EU air quality standard, then a decrease of hospital admissions of up to 2.6% would be observed. This is reiterated by Namdeo and Bell (2005) who reported that a significant number of respiratory hospital admissions are caused by NO_2 pollution. Various other studies have also been carried out examining the health impacts of NO_2 and it is again clear from these studies that exposure to NO_2 can be extremely harmful to human health, leading to a multitude of medical conditions and ultimately an increase in DALYs.

The literature has highlighted a potential avenue of investigation into the health impact of road emissions being produced in Dublin city. This avenue will use the available Bleeperbike data (or floating bike data (FBD)) as a source of determining the busiest cycle routes in the city, as well as using COPERT Street Level to estimate the emissions on these roads. This research will focus on the effect these pollutants could be having on cyclists and try to estimate the increase in DALYs this could cause. The approach and methods used in our study could be replicated in other across the world.

3. Methodology

This section details the various different methodologies employed in each component of the research. The research estimates emissions from the vehicles in the study area and then examines ambient air quality levels. It should be noted that these processes are different, and that the emissions estimation is not linked to the health impacts on the cyclist.

3.1. *FBD visualisation & traffic data*

Three months of journey data were provided by Bleeperbike for this study, November–January 2018. The data consisted of a series of data points recorded along each individual journey. The number of data points for each journey is dependent on the strength of the internet connection of the user's phone, as described previously. When interpreting the results presented in the paper, one should remember that the data was collected over the winter months. This may result in larger numbers of car trips and fewer bicycle trips due to the colder weather at this time of year in Dublin.

In order to present the FBD into an understandable format, Tableau was used. Tableau is a data visualisation software that is used for data science and business intelligence. Tableau can create a wide range of different visualisations to interactively present the data and showcase insights. It comes with tools that allow it to drill down data and see the impact in a much more visual format than other data processing programmes, such as Microsoft Excel. These visuals enable data presentation that can be easily understood.

Tableau was utilised here to take the raw data supplied by Bleeperbike in text format and create a map of the journeys made over the three months. All the individual data points were mapped using Tableau, with outliers and any points outside the county of Dublin being removed for efficiency purposes. The data points from the individual trips were then connected using a line that identified the data points by their trip ID characteristic which grouped the points to their associated journey. As the data points and line function do not take into account the layout of the road network when connecting together, the resultant map was a large series of criss-crossed lines that did not follow any sort of travel pattern nor were the individual journeys distinguishable without zooming to a very close level. To try and visualise the data in a way that illustrated the travel pattern of the cyclists, a density function map was used instead of a line. This density map groups data points together and creates a heat map based on the number of data points in close proximity to each other. This method of mapping the data provides a much clearer picture of the travel pattern of the cyclists and gives a strong indication of the busiest cycle corridors in Dublin City. A sample of the data given for one journey is shown in Table 1. The variable column represents the order of in which the GPS data point was recorded in the journey, so that they can be connected up at a later point. Table 1 also shows, the serial number is the same for each data point, meaning that the various points all share the same trip ID so that they can be grouped together as one journey.

Fig. 1 shows the density heat map produced in Tableau for the same November 2018 trip data. As it can be seen in Fig. 1, the density plot function provides a much more accurate representation of the busy cycle corridors, both by clearing up the map as well as effectively removing the far less frequent journeys made outside the city and canal corridors, allowing a more focussed map to be created. From this map five of the busiest sections of the city were then identified are indicated in Fig. 2, which was created using Google Maps. The start and end junctions of the five routes were identified to bound the length of the road considered in this study.

3.2. Dispersion modelling

An Operational Street Pollution Model (OSPM) was used to model the emission concentrations. OSPM software's are used to model ambient emissions concentrations. OSPM was used in this research to model the pollution concentrations at the street level. OSPM is developed by the Department of Environmental Science at Aarhus University (Aarhus University, 2018). The parameterization of flow and dispersion conditions in OSPM was developed based on extensive analysis of experimental data and model test (Berkowicz et al., 1997). OSPM calculates the concentration of exhaust emissions based on a combination of a Gaussian plume model for direct contribution and a box model to take into account the recirculation of the pollutants. In a street canyon, a wind vortex is formed such that the direction of the wind at street level is opposite to the flow above roof level. Because of this, the emitted pollutants from road traffic are transported towards the leeward side while the windward side is mainly exposed to recirculated pollutants and background pollution in the street (Berkowicz, 2000).

When setting the street collection, the configuration of each street or road link must be made individually. The user to set the height of the buildings along the road link, the width of the road, the length of the road on either side of the receptors and the orientation of the road link from North. The height of the receptors and any variation in building height along the road can also be set here. It should be noted other factors could impact upon concentrations such as trees placed in the built environment. However, in the approach used in this study, due limitations in the software, this was not considered.

Due to the fact that individual site visits could not be taken to observe the building heights along the roads (as this research was conducted during the COVID-19 pandemic), approximations were made using Google Maps and Google Street View to determine the geometry of the roads. The building heights were observed using Street View and one height was kept for the entire length of the road, instead of varying heights, for simplicity. Likewise, using Google Maps the width of the roads were measured and were kept as one constant width throughout the road length. The receptors were modelled at 1.75 m high to represent the concentrations at head height of the cyclists. The model also takes into account the dimensions of the roads and the density of buildings is also taken into account. The inclusion of building heights is a model input integrated into the software used.

The traffic editor in OSPM takes the traffic input as Average Daily Traffic rather than a single day of values, the data supplied by Dublin City Council was averaged to obtain median value for each hour of the day.

The vehicle breakdown was determined by taking the total hourly traffic flow on a given road link and using the vehicle breakdown in COPERT Street Level to obtain percentages of each vehicle type, and multiplying this percentage by the total traffic flow each hour. The vehicle breakdown given in COPERT Street Level is summarised in Table 2.

Table 1
FBD journey raw data sample.

Serial No	Start Time	End Time	Variable	GPS
100201154105830307103623	2018-11-01 07:45:04	2018-11-01 08:02:39	0	53.344122,-6.32143
100201154105830307103623	2018-11-01 07:45:04	2018-11-01 08:02:39	1	53.356708,-6.232401
100201154105830307103623	2018-11-01 07:45:04	2018-11-01 08:02:39	2	53.356711,-6.232388
100201154105830307103623	2018-11-01 07:45:04	2018-11-01 08:02:39	3	53.357276,-6.232874
100201154105830307103623	2018-11-01 07:45:04	2018-11-01 08:02:39	4	53.357384,-6.233121
100201154105830307103623	2018-11-01 07:45:04	2018-11-01 08:02:39	5	53.357176,-6.232735

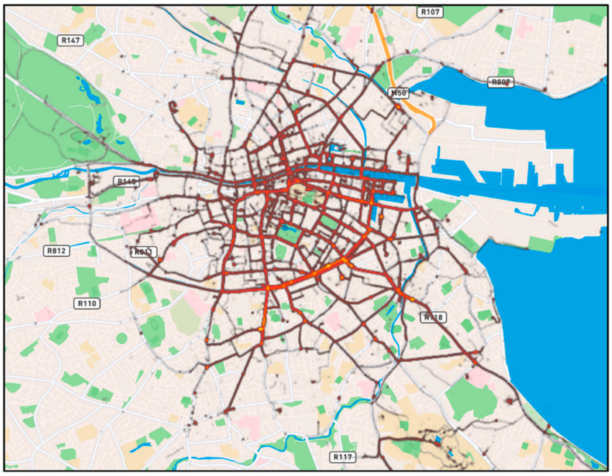

Fig. 1. November FBD journeys density map.

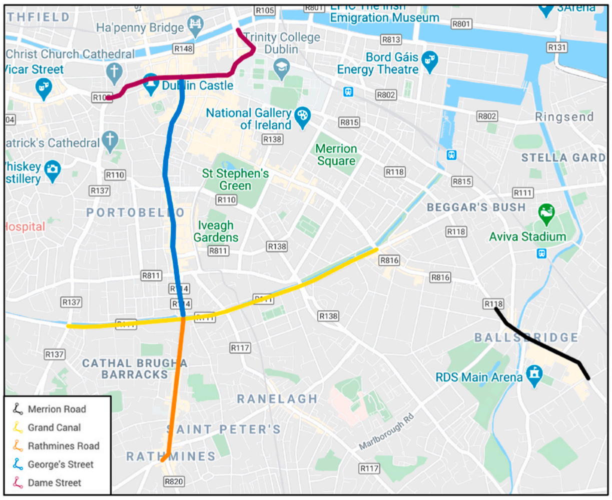

Fig. 2. The five busiest section of roads identified from the FBD

Once all this data had been compiled and input to OSPM, the model was run with an individual project for each of the four stretches of road identified previously. The results of these four models are presented later in the results section.

During the research it had been planned to validate the OSPM model by taking measurements at street levels. However, as mentioned previously this research was conducted during a lockdown period during the COVID 19 pandemic. This can be seen as a limitation of the work presented and this caveat should be considered when reviewing the results in the results section. However, a very similar OSPM model was validated in the study area by Tang et al. (2020).

3.3. *Estimation of health impacts*

The health effects of NO_2 were calculated using the WHO Burden of Disease (BOD) method from pollution concentrations (WHO, 2004). The burden of disease is usually measured in terms of the number of deaths and/or the DALY. DALY is expressed as the sum of

Table 2
Vehicle Breakdown used in OSPM.

Vehicle Type	Percentage Share
Passenger Cars	81.92%
Vans	15.32%
Trucks (<32T)	1.93%
Buses	0.83%

the YLL and YLD. YLD can be calculated as follows:

$$YLD = I*DW*L$$

Where *I* is the number of cases, *DW* is a disability weight on a scale of 0–1 and L is the average duration of disability in years. Due to the lack of available data, YLD were not calculated in this study. YLL is the number of years lost due to a premature death and calculated as follows:

$$YLL = D*L$$

Where *D* is the number of deaths and L is the standard life expectancy at age of death, i.e. the average years a person would have lived in the absence of the associated disease.

To calculate the YLL, the WHO BOD method must first be applied to obtain the variables *D* and *L*. The four main components of the BOD method are shown in Fig. 3.

Using these components, the expected number of deaths, *E* (*D* in the second equation above), can be calculated as follows (WHO, 2004):

$$E = AF*B*P \cdot (3.3)$$

Where *AF* is the attributable fraction of the health effects from air pollution for the exposed population, *B* is the population incidence of the given health effect (i.e. the deaths per 1000 people) is the underlying mortality rate and *P* is the relevant exposed population for the health effect. AF is calculated as follows:

$$AF = \frac{RR - 1}{RR}$$

Where RR is the relative risk at exposure compared to the reference level. RR is calculated as follows:

$$RR = exp(\beta(C - C_0))$$

Where β is an effect estimate that indicates the risk of an adverse health effect due to a one unit change in ambient air pollutant. *C* is the mean modelled concentration of pollutant in μg/m3 and C_0 is the baseline or counterfactual concentration also in μg/m3.

In some previous studies focussed in European cities, C_0 for NO_2 was taken as 20 $\mu g/m^3$ following HRAPIE recommendations. However, it has been indicated by some of the more recent studies that 20 $\mu g/m^3$ might be too high and that 10 μg/m3 was observed to be the lowest concentration at which a significant correlation between NO_2 concentration and health outcomes were observed (Raaschou-Nielsen et al., 2012). Therefore, two different values of C_0 were used in this study to calculate two different estimates. For all-cause mortality, b is taken as 0.001 for a 10 $\mu g/m^3$ increase in NO_2 concentration (WHO, 2013). This b value represents the estimation at the 95% confidence interval. Baseline mortality rate was taken as 8.1 per year per 1000 people (Central Statistics Office, 2016b). The relevant exposed population was taken as the number of cyclists in Dublin city on a daily basis, which is 95,000 people (Pollak, 2017).

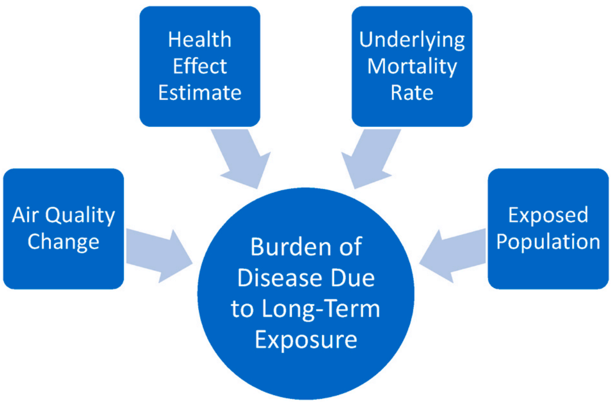

Fig. 3. Four components of the BOD method.

The following steps were taken to estimate the BOD values.

- Air Quality Change: This change is taken into account by comparing the modelled concentration results with the background concentration.
- Health Effect Estimate: This is an estimate of the risk of an adverse health effect or mortality due to a one-unit change in ambient air quality.
- Underlying Mortality Rate: This is the average number of people who die or suffer from a particular health effect over a given period of time in a given population.
- Exposed Population: This is the size of the population exposed to the pollution and the type of health effect considered.

3.4. Fleet change scenarios

In order to combat the pollution levels, many European cities have introduces Low Emission Zones (LEZs) to parts of the city. These LEZs are areas in which the most polluting vehicles are regulated or removed. LEZs are often the most effective measure that towns and cities can take to improve air pollution (Urban Access Regulations in Europe, 2020). Of the countries that have introduced LEZs, Belgium has one of the more drastic schemes in place, as it is in one of the most affected regions of air pollution in Europe. Belgium has introduced LEZs to Antwerp, Brussels and Ghent that will see the minimum engine requirements for passenger cars become Euro 3 for petrol and Euro 6 for diesel engines. This scenario was therefore selected as one of the fleet change scenarios modelled in COPERT Street Level. As a further investigative measure, another scenario where all diesel passenger cars have been removed was also modelled.

Scenario One: in order to split the share of vehicles accurately between the Euro categories allowed on the road, the percentage share of all diesel engines up to and including Euro 5 were summed and split evenly between Euro 6 and Euro 6+. Likewise for the petrol engines, the percentage share up to and including Euro 2 were summed and split evenly between the permissible classes.

Scenario Two: the percentage share of diesel engines in passenger cars was simply transferred to the petrol share.

Scenario Three: in this scenario the modelled in COPERT Street Level was a blanket reduction in the number of vehicles on the road by 10%. This was modelled by decreasing the input variables from the traffic counts by 10%. This was selected as it is representative of future goals of reducing transport emissions in the future in Ireland. This 10% was selected to represent a mode shift to walking, cycling and new micro-mobility modes, while this may seem ambitious, these types of modal shift are planned by Dublin City. This 10% reduction was applied to the traffic data input to the software and the fleet configuration remained the same to evenly apply the reduction. It is assumed that volume of people travelling will stay the same, just that they would travel by other modes.

4. Results

4.1. COPERT street level results

As described previously, a number of scenarios in which the fleet configuration changed were modelled in COPERT Street Level. Table 3 provides a description of the scenarios and gives each scenario a name so that they can be identified in the results.

In order to obtain accurate average daily emissions, a separate COPERT Street Model was compiled for each day of the week to correspond with the traffic data. Once all the models had been run and the results exported, the results from each day were averaged to give an accurate representation of the average daily emissions. Following this, the hourly emissions were then summed together to provide a daily total. This was done for all four scenarios and their daily total was plotted on the same bar chart to allow the comparison of the effect the scenarios had on the emissions. The NO_2 and $PM_{2.5}$ results are presented in Tables 4 and 5.

Examining at the results as a group, it can clearly be seen that scenario 2 is the most effective at reducing the emissions from the base scenario. While there is very little difference between scenario 1 and 2 in the $PM_{2.5}$ results, there is a considerable difference between the two scenarios in the NO_2 emissions.

As would perhaps be expected, scenario 3 does not have a large effect on the emission levels, as the 10% reduction in traffic appears to have simply caused a 10% reduction in emissions across the board. It could therefore be predicted that any further general reductions to the current fleet configuration would likely decrease the total emissions in a corresponding linear fashion.

Comparing the reduction in emissions between the base scenario and scenarios 1 and 2, it provides an interesting insight into the contribution of diesel engines to the overall emission levels. It can be seen that by removing diesel engine passenger cars completely in scenario 2, both the NO_2 and $PM_{2.5}$ emissions are reduced by roughly 50%, indicating that the diesel engine passenger cars are a major contributor to the overall pollution on Irish roads.

The scenario 1 results in particular shows how the older and lower Euroclass standard of the diesel engines compare to the latest Euro 6 and Euro 6+, as a significant portion of the overall emissions have been reduced by modelling a scenario where Euro 6 was the minimum diesel engine standard. Also contributing to these results is the removal of the petrol engine passenger cars in the Euro 1 & 2 categories, which will also help reduce the overall emissions.

It is interesting how in the $PM_{2.5}$ results there is only a difference of 0.43% in the reductions between scenarios 1 and 2, indicating that the higher Euro 6 and Euro 6+ diesel engines contribute very little to the overall pollution of $PM_{2.5}$, as the removal of these engine types is the only difference between the two scenarios. This is to say that substantial improvements have been made to passenger car diesel engines in recent years in terms of their $PM_{2.5}$ emission rates, especially when compared to the contribution of these same engine classes to the overall NO_2 emissions as demonstrated by the difference between scenarios 1 and 2 in the NO_2 results.

The trends in these results clearly demonstrate that while a reduction in the number of vehicles on the roads will result in a

Table 3
Fleet Configuration scenario descriptions.

Fleet Configuration	Description
Base Scenario	Current Fleet in Ireland
Scenario 1	Minimum Euro 6 diesel engine and Euro 3 petrol engine
Scenario 2	Complete removal of diesel engine passenger cars and minimum Euro 3 petrol engine required
Scenario 3	10% reduction of all traffic

Table 4
NO_2 COPERT street level results.

Road Link	Distance	Statistic	Base Scenario	Scenario 1	Scenario 2	Scenario 3
Dame Street	1.24 km	Daily NO_2 (tonne)	8.86	5.50	4.22	7.99
		Cost Implication	€50,395	€31,284	€24,003	€45,447
		Percentage Reduction	–	37.92%	52.37%	9.84%
Merrion Road	0.75 km	Daily NO_2 (tonne)	6.23	3.87	2.97	5.60
		Cost Implication	€35,436	€22,012	€16,893	€31,852
		Percentage Change	–	37.92%	52.37%	10.00%
Rathmines Road	0.88 km	Daily NO_2 (tonne)	8.24	5.12	3.93	7.42
		Cost Implication	€46,869	€29,122	€22,353	€42,204
		Percentage Reduction	–	37.92%	52.37%	10.00%
George's Street	1.53 km	Daily NO_2 (tonne)	7.74	4.81	3.69	6.97
		Cost Implication	€44,025	€27,359	€20,988	€39,645
		Percentage Reduction	–	37.92%	52.37%	10.00%

Table 5
$PM_{2.5}$ COPERT street level results.

Road Link	Distance	Statistic	Base Scenario	Scenario 1	Scenario 2	Scenario 3
Dame Street	1.24 km	Daily $PM_{2.5}$ (tonne)	0.250	0.132	0.131	0.225
		Cost Implication	€48,665	€25,695	€25,500	€43,799
		Percentage Reduction	–	47.44%	47.87%	10.00%
Merrion Road	0.75 km	Daily $PM_{2.5}$ (tonne)	0.176	0.092	0.091	0.158
		Cost Implication				
		Percentage Reduction	–	47.44%	47.87%	10.00%
Rathmines Road	0.88 km	Daily $PM_{2.5}$ (tonne)	0.233	0.122	0.121	0.210
		Cost Implication	€45,356	€23,749	€23,554	€40,879
		Percentage Reduction	–	47.44%	47.87%	10.00%
George's Street	1.53 km	Daily $PM_{2.5}$ (tonne)	0.219	0.115	0.114	0.197
		Cost Implication	€42,631	€22,386	€22,191	€38,348
		Percentage Reduction	–	47.44%	47.87%	10.00%

reduction in emissions, a priority needs to be put on removing the older outdated engine classes and diesel engines in particular, as they are the cause of a large portion of the emissions. Many Low Emission Zones in Europe have focussed primarily on the removal of some of the lowest Euro standard engines, and these results strongly reiterate that motive.

To try and give some context to these results, an economic impact due to the pollution levels has been estimated using the associated cost used by the Irish Department of Transport of €5688 per tonne of NO_2 and €194,660 for $PM_{2.5}$ (in urban areas) (DTTAS, 2016). On the road with the largest amount of NO_2 emitted, which was Dame Street, the total amount of NO_2 totals to roughly 8.9 tonnes per day. This figure demonstrates the scale of damage being done to both the environment and the public by road emissions.

4.2. OPSM dispersion modelling

The overall average concentrations over the year were taken as the results of interest. These average results are presented in Table 6 with the concentrations at both modelled receptors, located directly across the road from each other. The results in Table 6 is broken

Table 6
OSPM model results.

Route	Road Link	NO_2 Concentration (μg/m^3)		
		Side 1 of Road	Side 2 of Road	Average
Merrion Road	Pembroke-Anglesea	56.14	63.56	59.85
	Anglesea-Serpentine	51.71	57.33	54.52
	Serpentine-Sandymount	52.50	59.02	55.76
Rathmines Road	Canal-Leinster	45.91	42.99	44.45
	Leinster-Castlewood	44.71	41.91	43.31
	Castlewood-Rathgar	43.08	40.29	41.69
George's Street	Dame-Aungier	60.42	55.23	57.83
	Aungier-Cuffe	61.64	55.83	58.74
	Cuffe-Harcourt	50.93	57.21	54.07
	Harcourt-Canal	62.77	55.59	59.18
Dame Street	Burgh-Trinity	43.94	48.25	46.10
	Trinity-George's	49.34	55.57	52.46
	George's-Parliament	50.53	57.58	54.06
	Parliament-Christchurch	53.89	54.19	54.04

down The concentrations at both receptors on either side of the road were then averaged to obtain a mean value across the whole road, rather than at one particular receptor as these are effectively located on the walls of the roadside buildings which is not where the cyclists are cycle.

While there is no limit on NO_2 concentrations outlined by the EU or the WHO, there is as an annual average limit of 40 μg/m^3 of NO_2 (European Union, 2008). Table 6 shows that every single concentration modelled in OSPM exceeds the limit of 40 μg/m^3, and while this isn't the limit for NO_2 as mentioned, this is still a telling sign that emission concentrations may be above the EU limits in Dublin City.

4.3. Health impact assessment

The NO_2 concentration results from OSPM in the previous section were taken and used in the WHO BOD method in order to calculate the number of expected premature deaths (E), the years of life lost (YLL), relative risk (RR) and attributable fraction (AF). The results of these calculations for each of the road links are presented in Table 7 which gives results for two cases on each road link, one where the baseline concentration is 10 μg/m^3 and one where it is 20 μg/m^3.

Table 7 shows that the difference in the modelled concentrations from OSPM can have a significant effect on the difference in the number of expected premature deaths, as the results range from 17 to 30 premature deaths, or 24 to 37 premature deaths, depending on which value of C_0 is used. This results in a range of years of life lost between 182 and 331 years, or 264–412 years of life lost, again depending on which C_0 value is used.

The number of expected deaths on each road link are not singular cases independent of each other, as the road links are part of a larger road network where many cyclists will overlap on different road links. As well as this, the considered exposed cyclist population of 95,000 people was used in the calculations for each road link, when in fact this 95,000 represents the entire cyclist population of Dublin City. Therefore, it would be more accurate to look at an average of the number of expected deaths and subsequent years of life lost rather than a road by road case. Averaging the number of expected deaths from the results gives a mean value of either 271 or 353 years, once again depending on the C_0 value used once again.

These figures show that there is significant damage being done to the cyclists on these roads that are exposed to such concentrations. Not only are these emissions affecting the exposed cyclist population, but they are also doing damage to the pedestrians on these roads and others like them that have not been modelled. It could be argued that the pedestrian population are even more affected than the cyclists, as despite having a lower respiratory rate, which would result in a smaller volume of air being inhaled, the pedestrians are moving slower on the roads and would therefore be exposed to the emissions longer than the cyclists.

5. Conclusions

The results in this study show that there is a considerable surrounding the health impact of air pollution levels in Dublin city, and in particular amongst the cycling population. This can be said due to the health impact on the cyclist population estimated through an associated economic damage cost and the BOD method.

The results from the BOD method need very little explaining to understand their gravity. The results in this study indicate that as many as 37 premature deaths from the cyclist population could occur solely due to exposure to NO_2 pollution levels in Dublin city. It should be noted. That these results are independent of exposure to other air pollutants such as PM_{10}, $PM_{2.5}$, VOCs etc. which could significantly increase the number of premature deaths and corresponding years of life lost calculated in this study.

As shown in the COPERT Street Level results in this study, changing the Irish fleet configuration to remove outdated Euro class engines and diesel engines altogether, the mass of pollutants being emitted on Irish roads can be drastically reduced. Although it is difficult to estimate how an overall reduction in emissions affects the individual concentrations of emissions on the roads modelled using OSPM in terms of the magnitude of the reduction, it would definitely cause a decrease of some sort, even if the reduction pattern does not directly match those seen in the COPERT street Level results. However, it should also be noted that changing car fleets and more efficient EURO 6 class cars entering the market, will assist in reducing emissions and improving air quality.

The results from scenario 3 in the COPERT Street Level results were not found to have a large effect on the total emissions. However, there was still a decrease of 10% corresponding to the reduction in traffic, mainly due to how the scenario was constructed. As governments across Europe continue to push commuters towards more sustainable modes of transport such as public transport and cycling, these results show that these changes are not enough on their own to reduce the emissions levels by a satisfactory amount. Along with the shift in commuter mode choice, change must be implemented to keep the fleet of vehicles on the road to the highest standard in terms of Euro engine standards. While this is difficult to introduce in the private vehicle categories in the short term, as can be seen in the timeline of Low Emission Zones around Europe, efforts can be made to keep the public transport fleet up to date. And as the aim is to increase public transport numbers into the future, the contribution of these vehicles will only increase into the future, so it is imperative that these vehicles are as environmentally friendly as possible, to help reduce the adverse health impacts and subsequent deaths on the exposed population. Further efforts to create barriers for cyclist and pedestrians can also mitigate these impacts by using green buffer zones.

Initially, this study set out to use the FBD to determine both cyclist patterns and figures in Dublin city. While it was initially successful in determining the patterns through the use of a density map, at a later point in the study when the exposed cyclist population was being determined it was hoped that the FBD could be used to determine the volume of cyclists on each road link. Unfortunately, due to the nature of the way the GPS data is recorded, it would have been extremely inaccurate to determine the number of cyclists this way, as the mapped journeys are simple straight lines connecting data points to each other and do not follow the road

Table 7
Burden of disease results.

Route	Road Link	C_0 (μg/m^3)	C (μg/m^3)	RR	AF	E	YLL
Merrion Road	Pembroke-Anglesea	10	59.85	1.0511	0.04863	37	412
		20		1.0407	0.03907	30	331
	Anglesea-Serpentine	10	54.52	1.0455	0.04354	34	369
		20		1.0351	0.03393	26	287
	Serpentine-Sandymount	10	55.76	1.0468	0.04473	34	379
		20		1.0364	0.03513	27	297
Rathmines Road	Canal-Leinster	10	44.45	1.0351	0.03386	26	287
		20		1.0248	0.02415	19	204
	Leinster-Castlewood	10	43.31	1.0339	0.03276	25	277
		20		1.0236	0.02304	18	195
	Castlewood-Rathgar	10	41.69	1.0322	0.03119	24	264
		20		1.0219	0.02145	17	182
George's Street	Dame-Aungier	10	57.83	1.0490	0.04670	36	395
		20		1.0385	0.03712	29	314
	Aungier-Cuffe	10	58.74	1.0499	0.04757	37	403
		20		1.0395	0.03799	29	322
	Cuffe-Harcourt	10	54.07	1.0451	0.04311	33	365
		20		1.0347	0.03350	26	284
	Harcourt-Canal	10	59.18	1.0504	0.04799	37	406
		20		1.0400	0.03842	30	325
Dame Street	Burgh-Trinity	10	46.10	1.0368	0.03545	27	300
		20		1.0264	0.02576	20	218
	Trinity-George's	10	52.46	1.0434	0.04157	32	352
		20		1.0330	0.03193	25	270
	George's-Parliament	10	54.06	1.0450	0.04310	33	365
		20		1.0346	0.03348	26	283
	Parliament-Christchurch	10	54.04	1.0450	0.04308	33	365
		20		1.0346	0.03347	26	283

network. It is therefore impossible to determine the number of cyclists travelling on any given road as the journeys do not accurately map the route of the cyclist. It is for this reason that any future studies that intend to use FBD in a similar fashion to this study will most likely be only able to use it for indicative purposes rather than quantitative.

While this study has successfully calculated and discussed the health impact of air pollution on the exposed cyclist population as it set out to do, there were a number of issues relating to some of the data inputs in OSPM that could be investigated and improved upon to increase the accuracy and reliability of the results. While this investigation would have ideally been undertaken during the course of this study, several difficulties were encountered during the recent COVID-19 outbreak, as discussed previously. Therefore, if this study were to be repeated or improved upon in the future, several areas such as the meteorological data, the street geometry data and the fleet configuration data should be investigated further to obtain a more accurate and relevant dataset that could be input to OSPM to produce more localised and reliable results. As well as this, a significant amount of time should be taken to become accustomed to OSPM itself, as it is an extremely extensive programme with many elements of it being unexplored in this study. It is anticipated that further investigation into the workings of OSPM in terms of its required inputs and available outputs would allow the user to create an in-depth model of the emission concentrations in Dublin city for a much wider variety of pollutants than examined in this study. This would then lead to a more comprehensive calculation of the overall health impact of air pollution on the exposed population, as it would include a wider set of pollutants.

CRediT authorship contribution statement

Ian Smith: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Brian Caulfield:** Conceptualization, Methodology, Software, Validation, Resources, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration. **Shreya Dey:** Methodology, Writing - review & editing.

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References

Aarhus University, 2018. Operational street pollution model-OSPM. Department of Environmental Science. http://envs.au.dk/en/knowledge/air/models/ospm/. Last accessed on: 04.03.

Berkowicz, R., 2000. OSPM-A parameterised street pollution model. Environ. Monit. Assess. 65, pp323–331.

Berkowicz, R., Hertel, O., Larsen, S.E., Sørensen, N.N., Nielsen, M., 1997. Modelling Traffic Pollution in Streets. Ministry of Environment and Energy National Environmental Research Institute.

Caulfield, B., 2014. Re-cycling a city - examining the growth of cycling in Dublin. Transport. Res. Pol. Pract. 61, 216–226.
Carroll, P., Dey, S., Caulfield, B., Pilla, F., Ghosh, B., Ahern, A., Morgenroth, E., 2016. Review of Environmental and Transportation Modelling Methods and Development of Transport Emissions Models. Irish Environmental Protection Agency.
Central Statistics Office, 2016a. Commuting in Ireland. Central Statistics Office, Dublin.
Central Statistics Office, 2016b. Deaths Registered by County of Residence of deceased, 2015. Central Statistics Office, Dublin.
Clancy, L., Goodman, P., Sinclair, H., Dockery, D.W., 2002. Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study. Lancet 360, 1210.
Chaloulakou, A., Mavroidis, I., Gavriil, I., 2008. Compliance with the annual NO2 air quality standard in Athens. Required NOx levels and expected health implications. Atmos. Environ. 42, pp454–465.
Dey, S., 2018. Modelling of Vehicular Emission and Their Potential Environmental, Health, and Economic Impacts. PhD, Trinity College Dublin.
Dublin City Council, 2020. Latest Dublin bikes figures [online]. http://www.dublinbikes.ie/Magazine/Reports/Just-Eat-dublinbikes-latest-figures. Last accessed on: 04.06.2020.
European Environment Agency, 2014. Air Pollution Fact Sheet. European Environment Agency, Wexford, Ireland.
Environmental Protection Agency, 2020. Ireland's Provisional Greenhouse Gas Emissions 1999-2019. Environment Agency, Wexford, Ireland.
European Environment Agency, 2017. Air Quality in Europe - 2017 Report. Wexford, Ireland.
European Environment Agency, 2018. Air Quality in Europe - 2018 Report. Wexford, Ireland.
Emisia, 2019. COPERT versions [online]. https://www.emisia.com/utilities/copert/versions/Last accessed on: 04.06.2020.
Emisia, 2020. Utilities [online]. https://www.emisia.com/utilities/Last accessed on: 04.06.2020.
Fann, N., Coffman, E., Timin, B., Kelly, J.T., 2018. The estimated change in the level and distribution of PM2. 5-attributable health impacts in the United States: 2005–2014. Environ. Res. 167, pp506–514.
Gkatzoflias, D., Kouridis, C., Ntziachristos, L., Samaras, Z., 2006. COPERT 4: Computer Programme to Calculate Emissions from Road Transport. European Environment Agency.
Héroux, M.-E., Anderson, H.R., Atkinson, R., Brunekreef, B., Cohen, A., Forastiere, F., Hurley, F., Katsouyanni, K., Krewski, D., Krzyzanowski, M., Künzli, N., Mills, I., Querol, X., Ostro, B., Walton, H., 2015. Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe project. Int. J. Publ. Health 60, 619–627.
Martinez, G.S., Spadaro, J.V., Chapizanis, D., Kendrovski, V., Kochubovski, M., Mudu, P., 2018. Health impacts and economic costs of air pollution in the metropolitan area of Skopje. Int. J. Environ. Res. Publ. Health 15, 626.
Namdeo, A., Bell, M., 2005. Characteristics and health implications of fine and coarse particulates at roadside, urban background and rural sites in UK. Environ. Int. 31, pp565–573.
Nta, 2017–2019. National Household Travel Survey. NTA, Dublin Ireland.
Pollak, S., 2017. Number of daily Dublin cyclists doubles to more than 95,000. Ir. Times.
Raaschou-Nielsen, O., Andersen, Z.J., Jensen, S.S., Ketzel, M., Sørensen, M., Hansen, J., Loft, S., Tjønneland, A., Overvad, K., 2012. Traffic air pollution and mortality from cardiovascular disease and all causes: a Danish cohort study. Environ. Health 11, 60.
Song, C., He, J., Wu, L., Jin, T., Chen, X., Li, R., Ren, P., Zhang, L., Mao, H., 2017. Health burden attributable to ambient PM2. 5 in China. Environ. Pollut. 223, pp575–586.
Tao, Y., Huang, W., Huang, X., Zhong, L., Lu, S.-E., Li, Y., Dai, L., Zhang, Y., Zhu, T., 2012. Estimated acute effects of ambient ozone and nitrogen dioxide on mortality in the Pearl River Delta of southern China. Environ. Health Perspect. 120, pp393–398.
Tang, J., McNabola, A., Misstear, B., 2020. The potential impacts of different traffic strategies on air pollution and public health for a more sustainable city: a modelling case study from Dublin, Ireland. Sustainable Cities and Society 60, 102229.
United States Environmental Protection Agency, 2019. Frequesnt questions about volkswagen violations. https://www.epa.gov/vw/frequent-questions-about-volkswagen-violations Last accessed on: 04.11.2019.
Urban Access Regulations in Europe, 2020. What are low emission zones? [Online]. https://urbanaccessregulations.eu/low-emission-zones-main/what-are-low-emission-zones Last accessed on: 04.06.2020.
World Health Organisation, 2014. 7 million premature deaths annually linked to air pollution. https://www.who.int/mediacentre/news/releases/2014/air-pollution/en/Last accessed on: 04.11.2019.
World Health Organisation, 2018. Ambient (outdoor) air pollution. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health. Last accessed on: 04.11.2019.
World Health Organisation, 2003. Assessing the environmental burden of disease at national and local levels. In: Prüss-Üstün, A., Campbell-Lendrum, D., Corvalán, C., Woodward, A. (Eds.), Environmental Burden of Disease Series.
Yin, H., Pizzol, M., Xu, L., 2017. External costs of PM2. 5 pollution in Beijing, China: uncertainty analysis of multiple health impacts and costs. Environ. Pollut. 226, pp356–369.