Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
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INTEGRATED TRANSPORTATION AND LAND USE REGRESSION MODELLING FOR NO_2 MITIGATION

VOLUME 1

Aonghus Ó Domhnaill

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Dissertation submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy (PhD) in Civil, Structural and Environmental Engineering.

Submission Date: 30th April 2022

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Abstract

The transport industry has been identified as one of the main contributors to Nitrogen Dioxide (NO_2) pollution in Ireland. Diesel fuelled vehicles emit significantly greater amounts of NO_2 in comparison to any other fuel type. In 2008, car taxation in Ireland underwent a significant change from an engine size based system to a Carbon Dioxide (CO_2) emission rate based system. This resulted in a significant transition towards diesel fuelled vehicles in response to taxation change which typically emit less CO_2 than other fuel types. The majority of vehicle categories are now diesel powered such as small public service vehicles, large public service vehicles and heavy goods vehicles are diesel powered and the car fleet is also pre-dominantly diesel powered. Whilst air quality in Ireland is considered relatively good in comparison to other countries in Europe this dependency on diesel fuelled vehicles is of concern as NO_2 monitoring stations in Ireland continue to record NO_2 concentration levels close to the European Union's Directive on Ambient Air Quality and Cleaner Air for Europe (2008/50/EC) limit values and any change in conditions (such as adverse weather conditions or increased traffic levels or other pollution sources) could lead to an exceedance of these limit values. The World Health Organisation reduced their annual limit value for NO_2 in September 2021, due to the increasing evidence in literature which identify links between NO_2 exposure and various health effects (respiratory and cardiovascular) in the population. The revised limit by the World Health Organisation considers levels of NO_2 in excess of 10 $\mu g/m^3$ to be harmful to the population. In the Irish context, only rural locations are achieving this revised limit value, therefore, identifying mitigation measures to reduce NO_2 across wide regions of the country are necessary to reduce the impacts of air pollution on the health of the population.

This research develops an enhanced Wind Sector Land Use Regression (WS-LUR) model to estimate NO_2 concentrations across Ireland, in areas where monitoring of air pollution is not available. The model incorporates details of the vehicle fleet breakdown within the WS-LUR model equation to weight vehicle type flows based on the emission rates of the vehicle type, which differentiates routes with different proportions of heavier emitting vehicles (such as haulage route). The model was developed in Excel and provides a simpler approach for NO_2 concentration estimates to the same level of accuracy as detailed emissions modelling software. The model has two modelling approaches, the pre-set approach which utilises stored variable information within the model and therefore can calculate NO_2 concentrations automatically once a location is specified, and a manual entry

approach which allows a modeller to analyse any location by inputting values manually for each of the predictor variables within the model.

The model was validated against measured concentrations from numerous locations in Ireland for the 2016 to 2018 period and also validated in an additional analysis of the unique scenario / environment presented by the COVID lockdown period in 2020. A number of mitigation measures to improve air quality in Ireland that target model variables were identified and analysed using the enhanced WS-LUR model. These mitigation measures included; the relocation of a major business hub to reduce commercial properties in an area and reduce traffic traveling to and from the area; the removal of diesel fuelled vehicles from the small public service vehicle and large public service vehicle fleets; the construction of a ring road around a major city to provide an alternative route for traffic to bypass the city centre area and finally the introduction of a Low Emission Zone (LEZ) within Dublin City to influence transport mode choice and the number of vehicles entering the city centre area.

The original model captured 78% of spatial variability in NO_2 and when checked against 2016 to 2018 conditions both the original model approach and the enhanced WS-LUR achieved cross-validation R^2 of 76% confirming the accuracy was not impacted by the addition of a weighting which accounts for the vehicle fleet breakdown. The analysis of the COVID lockdown period also reinforced the confidence in the enhanced WS-LUR model to accurately model concentrations in unique scenarios, with a cross-validation R^2 of 82% when excluding an outlier in the analysis. The changes in major route flows were the main contributors to the reductions in concentrations whilst the changes in weather conditions during the COVID lockdown period contributed to increases in concentrations across the majority of locations. The model successfully estimated the changes in concentrations due a number of mitigation measures. Positive results were achieved in the most heavily polluted areas in each of the mitigation measures (Dublin City Centre for the LEZ, Blanchardstown business hub relocation and the public service vehicles diesel removal measures; South Cork City for the Cork Ring Road mitigation measure), areas which are currently experiencing pollution levels close to the Directive 2008/50/EC limits.

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisors Prof. Margaret O'Mahony and Prof. Brian Broderick for their continued support, valuable guidance and encouragement throughout the duration of my PhD research.

I would like to thank the Environmental Protection Agency for funding this research. Also, I would like to thank all of the steering committee members of the EPA project for assisting with data requests and their guidance over the duration of the project.

Ba mhaith liom mile buíochas a ghlacadh le mo chlann, go h-áirithe mo mháthair Kathleen a bhí ansin i gconaí dhom le haghaidh mé a spreagadh nuair a bhí tréimhsí deacair.

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List of Abbreviations

A	All Euro Classes
α_j	Regression Coefficient
α_0	Constant
AADT	Annual Average Daily Traffic
$AADT_V$	Annual Average Daily Traffic for Vehicle Type, V
AAT	Alpha-1 Antitrypsin
ADT	Average Daily Traffic
AM	AM Peak Time Period / Ante Meridiem
ATC	Automatic Traffic Counter
BC	Black Carbon
BC	Buses (Compressed Natural Gas)
BS	Buses (Standard)
C	Ambient Wind Dependent Background Pollutant Concentration
C	Compressed Natural Gas
CN	Conventional
CO	Carbon Monoxide
COMEAP	Committee on the Medical Effects of Air Pollutants
COPD	Chronic Obstructive Pulmonary Disease (COPD)
CORINE	Coordinated Information on the Environment
CS	Buses (Coaches Standard)
CSO	Central Statistics Office
d	Distance to Receptor Location
D	Diesel
d_i	Distance from Point, i to Receptor Location,
d_n	Distance between Study Location and Point, n
DL	Diesel Large
DM	Diesel Medium
DMAX	Diesel >32 Tonnes
DPF	Diesel Particulate Filter

DS	Diesel Small
D16	Diesel 7.5 – 16 Tonnes
D32	Diesel 16 – 32 Tonnes
D7.5	Diesel <7.5 Tonnes
e	Euro Class
E	Ethanol E85
e_A	Average Emission from All Vehicles in a Study Period
E_k	Emission Weighting for Vehicle Category, k
$E_{PC,PMIN}$	Percentage of Petrol Passenger Cars with Engine Capacity within Mini Range (<1000 c.c.)
e_v	Average Emission from Vehicle Type, v in a Study Period
$E_{v,s}$	Engine Capacity Percentage
EC	Elemental Carbon
$EC_{v,y,e}$	Estimated Euro Class Percentage
ECE1	Pre-Euro Class (ECE 15/00-01)
ECE2	Pre-Euro Class (ECE 15/02)
ECE3	Pre-Euro Class (ECE 15/03)
ECE4	Pre-Euro Class (ECE 15/03)
ED	Emergency Department
EEA	European Environmental Agency
EEV	Enhanced Environmentally Friendly Vehicle
EII	Euro II
EIII	Euro III
EIV	Euro IV
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
ERTDI	Environmental Research Technological Development and Innovation Programme
EU	European Union
EV	Euro V
EVI	Euro VI

E1	Euro 1
E2	Euro 2
E3	Euro 3
E4	Euro 4
E4&L	Euro 4 and Later
E5	Euro 5
E6	Euro 6
E6-2016	Euro 6 (≤2016)
E6-2017	Euro 6 (≤2017)
E6-2019	Euro 6 (2017 - 2019)
E6-2020	Euro 6 (2018 - 2020)
f	Fuel Type
F_i	Trip Category
f_n	Meteorological Variable Value at Point, n
$F_{PC,P}$	Percentage of Passenger Cars Fuelled by Petrol
$F_{v,f}$	Fuel Type Percentage
$f\text{-}NO_2$	NO_2 Fraction
GAINS	Greenhouse Gas Air Pollution Interaction and Synergies
GDP	Gross Domestic Product
GIS	Geographic Information System
H	Hybrid Petrol
HC	Hydrocarbons
HDV	Heavy Duty Vehicle (Goods Vehicles Greater than 3.5 Tonnes Unladen Weight)
HPL	Hybrid Petrol Large
HPM	Hybrid Petrol Medium
HPS	Hybrid Petrol Small
i	Wind Sectors
IDWVKT	Inverse Distance Weighted Vehicle Kilometres Travelled
$IDWVKT_V$	Inverse Distance Weighted Vehicle Kilometres Travelled for Vehicle Type, V

ISA	Integrated Science Assessments
j	Terms of the Regression Equation
LAT	Lower Assessment Threshold
LCV	Light Commercial Vehicle
LEZ	Low Emission Zone
LGV	Light Goods Vehicle (Goods Vehicles Less than 3.5 Tonnes Unladen Weight)
LNT	Lean NO_X Trap
LPG	Liquefied Petroleum Gas
LPSV	Large Public Service Vehicle
LT	Lunch Time Time Period
M	Motorcycle
Mop	Moped Euro Class
Mot	Motorcycle Euro Class
n	Group Number
n	Number of Dependent Points / Triangulation Accuracy
N_k	Number of Vehicles in Category, k
N_2	Nitrogen (Molecule)
NH_3	Ammonia
NMHC	Non-Methane Hydrocarbons
NO	Nitric Oxide
NO_X	Nitrogen Oxides
NO_2	Nitrogen Dioxide
NTA	National Transport Authority
O_2	Oxygen (Molecule)
O_3	Oxygen (Molecule)
OECD	Organisation for Economic Cooperation and Development
OGV	Ordinary Goods Vehicles
OGV_1	Ordinary Goods Vehicles with Two / Three Axles
OGV_2	Ordinary Goods Vehicles with Four or More Axles (Includes OGV_1 Vehicles with Trailers)

OL	Open Loop
OP	Off Peak Time Period
OSI	Ordnance Survey Ireland
P	Petrol
P_j	Predictor Variable
$P_{1,e}$	Vehicle Sub-Type Euro Class Percentage (Sub-Type Group 1)
$P_{2,e}$	Vehicle Sub-Type Euro Class Percentage (Sub-Type Group 2)
PC	Passenger Car
$PC_{PMIN,E4}$	Percentage of Total Vehicles Categorised as Euro 4 Petrol Mini Passenger Cars
PCRS	Primary Care Reimbursement Services
PCU	Passenger Car Unit
PECE	Pre-ECE Euro Class
PL	Petrol Large
PM	PM Peak Time Period / Post Meridiem
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter (less than 2.5 micrometers)
PM_{10}	Particulate Matter (less than 10 micrometers)
PMED	Petrol Medium
PMIN	Petrol Mini
PRE	Pre-Euro; Pre-Euro / Euro 1; Pre-Euro / Euro I; Pre-Euro / Euro 1 / Euro 2; Pre-Euro / Euro I / Euro II
PS	Petrol Small
PSV	Public Service Vehicle
PtH	Period to Hour Factor
RAINS	Regional Air Pollution Information and Simulation
s	Vehicle Sub-Type (Engine Capacity Category or Unladen Weight Category)
S_A	Percentage Vehicles Categorised as Vehicle Type, v and Sub-Type Group 1
$S_{E4\&L}$	Percentage Vehicles Categorised as Vehicle Type, v and Sub-Type Group 2
SCR	Selective Catalytic Reduction
SE	Standard Error

SO_2	Sulfur Dioxide
SPSV	Small Public Service Vehicle
SR	School Run Time Period
STRIVE	Science, Technology, Research and Innovation for the Environment Programme
T	Time Period
$T_{PC,PMIN,2,E4}$	Percentage of Petrol Mini Passenger Cars Categorised as Euro 4
T_{PtH}	Period to Hour Factor for Time Period, T
$T_{v,s,n,e}$	Vehicle Sub-Type Breakdown by Euro Class
THC	Total Hydrocarbons
TII	Transport Infrastructure Ireland
TILDA	The Irish Longitudinal Study on Ageing
$U_{v,s}$	Unladen Weight Percentage
UAT	Upper Assessment Threshold
UFP	Ultrafine Particles
ULEZ	Ultra Low Emission Zone
v	Vehicle Type
V_{PC}	Percentage of Total Vehicles Categorised as Passenger Cars
V_{PCU}	Vehicle Flow during Time Period, T
v_s	Vehicle Sub-Type Percentage
$v_{s,e}$	Calculated Euro Class Percentage
V_v	Vehicle Type Percentage
V_T	Vehicle Flow during Time Period, T
VKT	Vehicle Kilometres Travelled
VKT_V	Vehicle Kilometres Travelled by Vehicle Type, V
Wf_i	Fraction of Hourly Wind Directions within Sector, i
W_v	Weighting Factor Percentage
WHO	World Health Organisation
WS-LUR	Wind Sector Land Use Regression
x_n	X Co-ordinate of Point, n

y	Year / Time Period
y_n	Y Co-ordinate of Point, n
2S-MAX	2-Stroke >50cm^3
2S-50	2-Stroke <50cm^3
2010-12	2010 - 2012
4S-MAX	4-Stroke >750cm^3
4S-250	4-Stroke <250cm^3
4S-50	4-Stroke <50cm^3
4S-750	4-Stroke 250 - 750cm^3

1. Introduction

1.1. Background

Short-term and long-term air pollution exposure can have significant impacts on health, with numerous health effects (cardiovascular and respiratory) linked to one or a number of air pollutants (World Health Organisation, 2021; United States Environmental Protection Agency, 2016). The main air pollutants which have sufficient evidence to confirm links to health effects are Particulate Matter (PM), Ozone (O_3), Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2). PM can be anthropogenic or it can originate from natural sources and is typically subcategorised by particle size such as PM10 and PM2.5, which represent particles less than or equal to 10 µm in diameter and fine particles less than or equal to 2.5 µm in diameter (United States Environmental Protection Agency, 2021). O_3 is formed when a number of pollutants (nitrogen oxides (NO_X), volatile organic compounds (VOCs), industrial emissions) react with sunlight (World Health Organisation, 2021). The transport and energy sectors as well as residential heating are common sources of NO_2 (World Health Organisation, 2021). SO_2 is typically formed during the combustion of fossil fuels such as residential heating, the energy sector and transport (World Health Organisation, 2021). The World Health Organisation confirmed that 99% of the entire population in 2019 were located in areas of poor air quality (areas which exceeded the World Health Organisation guidance limits for pollutants) and in 2016, ambient air pollution accounted for 4.2 million premature deaths (World Health Organisation, 2021).

Figure 1.1 shows the death rates (per 100 000 population) of European countries which are attributable to air pollutant exposure. Western European (Spain, Portugal, France, Luxembourg and Ireland) and Scandinavian countries (Iceland, Norway, Sweden and Finland) had less than 28 deaths per 100 000 population which were attributable to air pollution exposure whilst death rates for the remaining countries ranged between 31 and 125 air pollution related deaths per 100 000 population (World Health Organisation, 2018). Ireland has the 5th lowest death rate attributable to air pollution of European countries at approximately 21 deaths per 100 000 population, behind only the Scandinavian countries (Finland, Norway, Sweden and Iceland) (World Health Organisation, 2018).

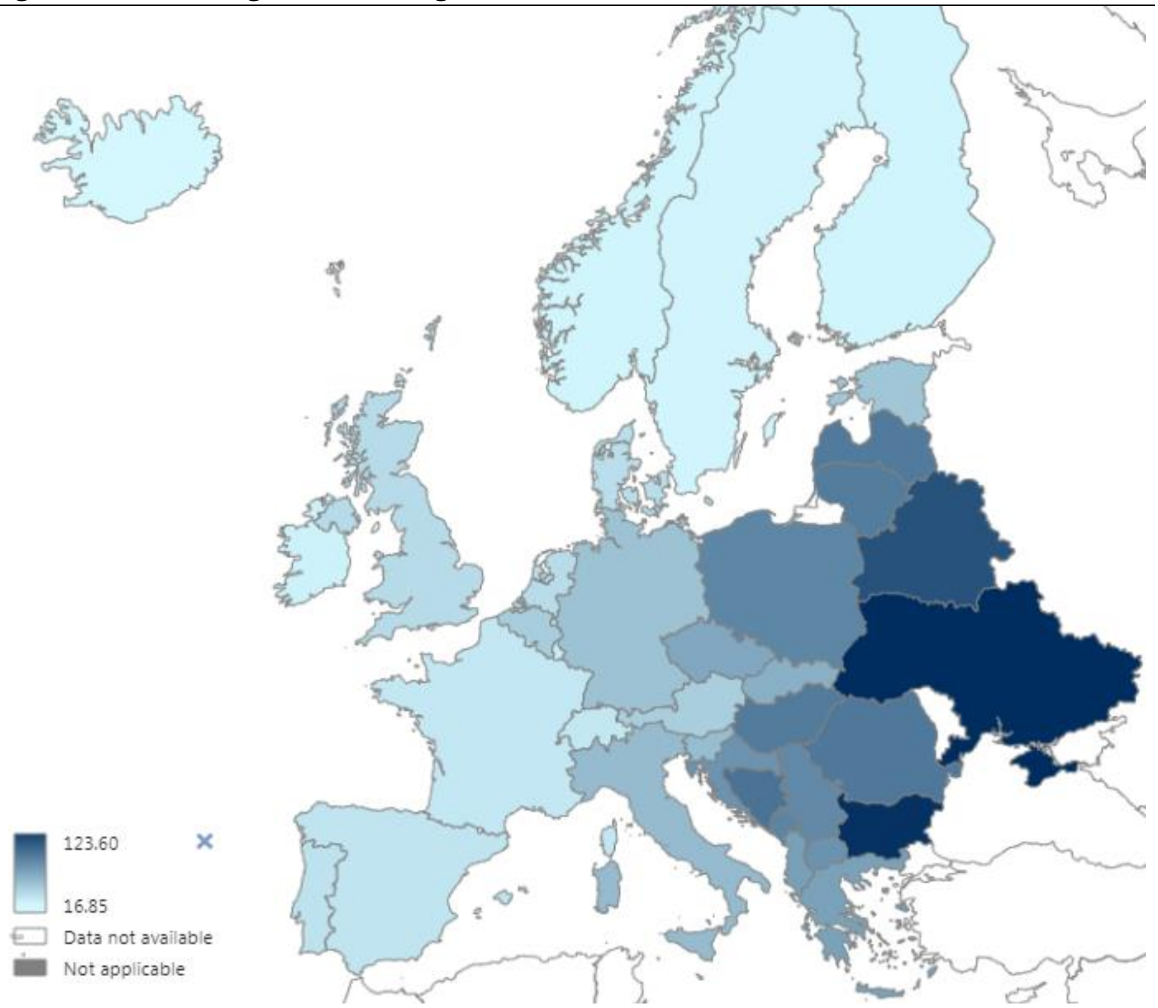


Figure 1.1: Ambient Air Pollution Attributable Death Rate (Per 100 000 Population) (World Health Organisation, 2018)

Years of Life Lost (YLLs) represent the combined number of years that the population would have lived if not for a particular health effect (World Health Organisation, 2022). The YLLs were significantly greater in the largest countries by area in Europe (excluding Scandinavian countries) such as Spain, France, Germany, Poland, United Kingdom, Belarus, Ukraine and Romania with YLLs in the range of 110 000 and 1 100 000 years whilst the remaining countries such as Netherlands, Belgium, Luxembourg, Portugal, Ireland, Adriatic countries, Baltic countries and Scandinavian countries had less YLLs ranging between 800 and 85 000 years, as shown in Figure 1.2 (World Health Organisation, 2018). Ireland had the 9^{th} smallest YLLs of all European countries at approximately 16 000 years (World Health Organisation, 2018).

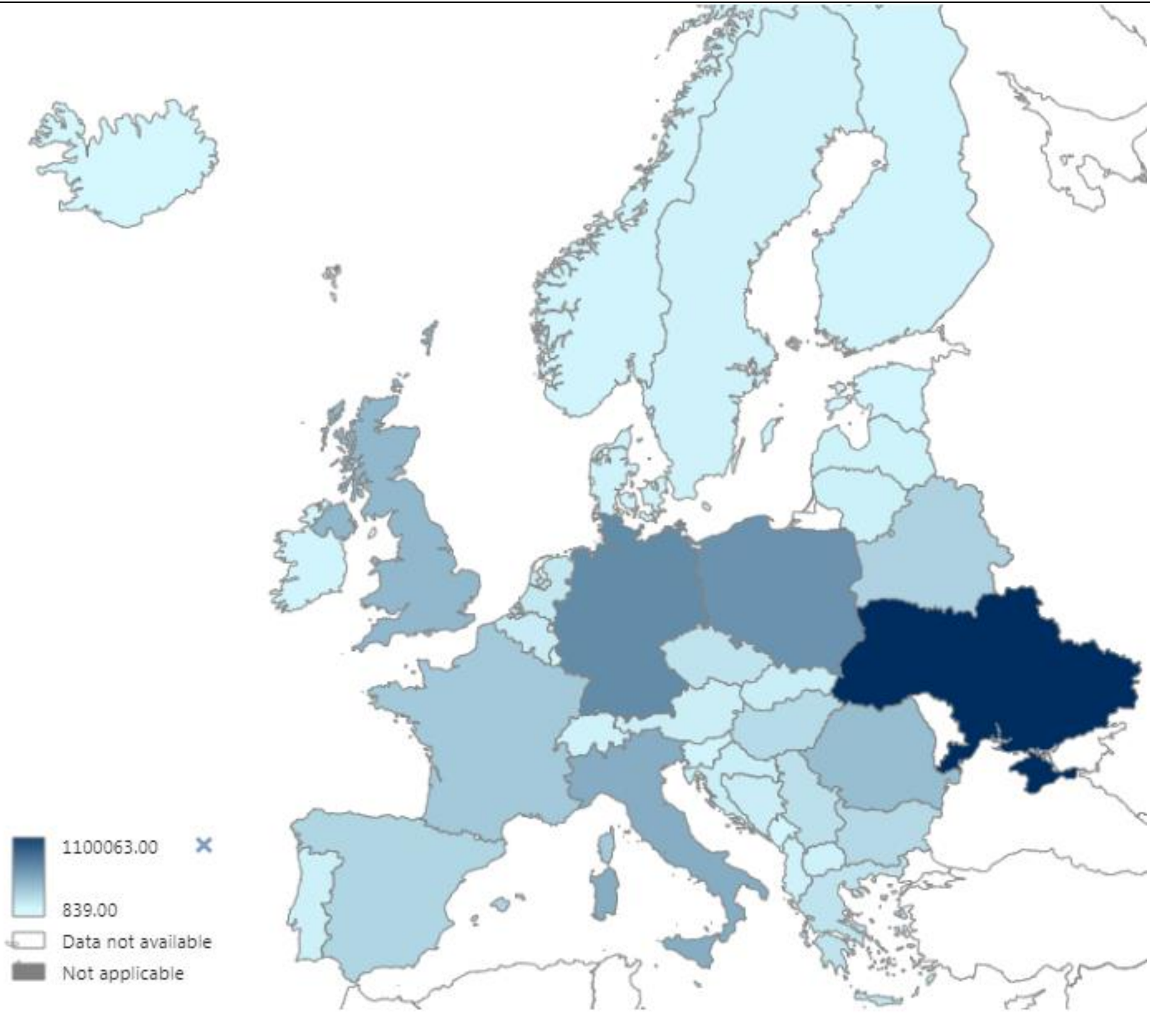


Figure 1.2: Ambient Air Pollution Attributable Years Life Lost (World Health Organisation, 2018)

Disability-Adjusted Life Years (DALYs) represent the combined number of YLLs and the number of years which are spent by the population with a disability or at less than full health due to a particular disease (World Health Organisation, 2022). DALYs (per 100 000 population) due to air pollution in European Countries are shown in Figure 1.3 and it presents significantly greater numbers of DALYs in Eastern European countries, ranging from approximately 1 100 to 2 600 years (World Health Organisation, 2018). Western European and Scandinavian countries ranged between 250 and 800 DALYs per 100 000 population. Ireland has the 5th lowest number of DALYs of all European countries at 360 years per 100 000 population, behind only the Scandinavian countries (Finland, Norway, Sweden and Iceland) (World Health Organisation, 2018).

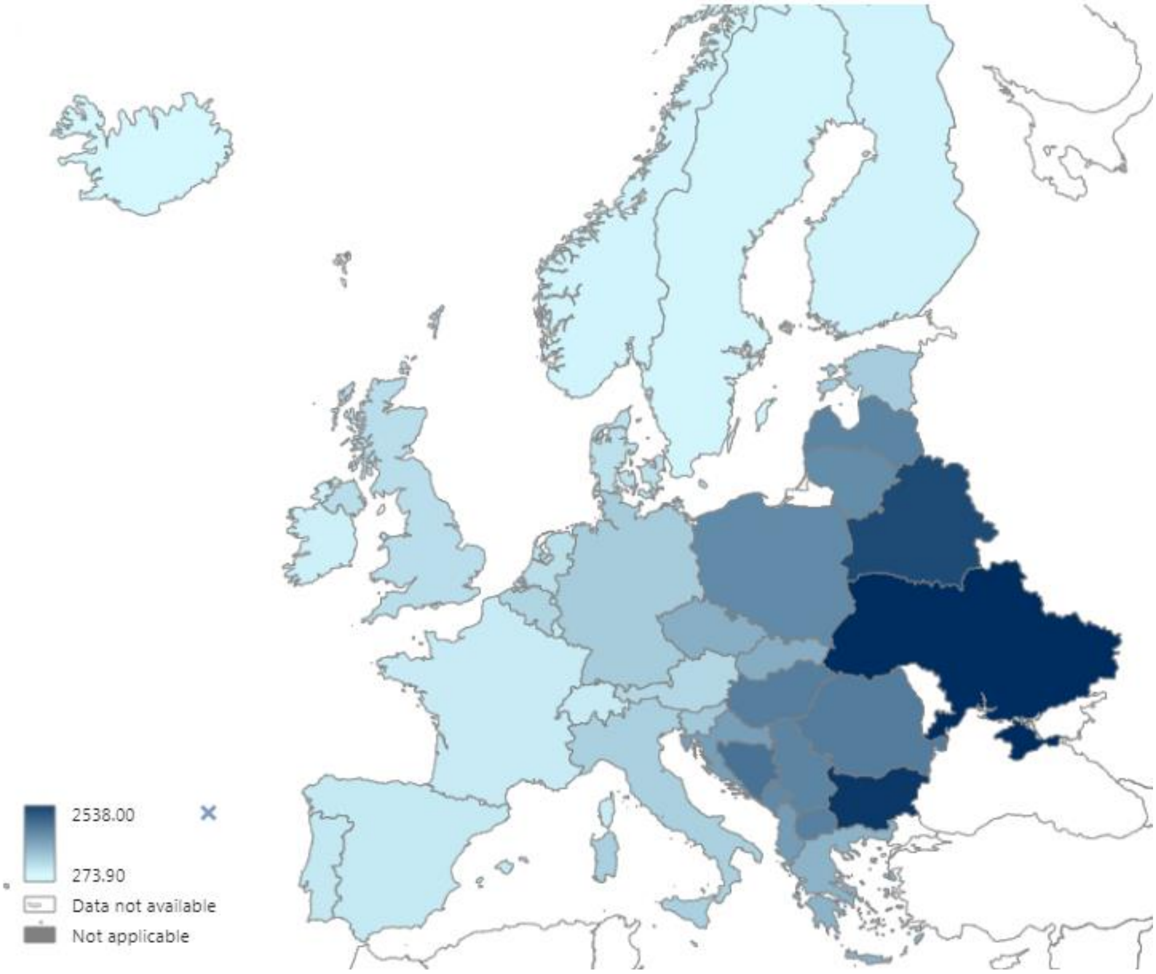


Figure 1.3: Ambient Air Pollution Attributable DALYs (Per 100 000 Population) (World Health Organisation, 2018)

As shown in Figure 1.1 to Figure 1.3, in comparison to many other European Union (EU) countries, the standard of air in Ireland is of higher quality but in relation to NO_2, the ambient concentrations can be close to the limit values within the EU standards (European Union, 2008). Due to the update of World Health Organisation guidelines in September 2021, levels of NO_2 exceed the World Health Organisation limits (World Health Organisation, 2021) in the majority of locations and adverse weather conditions or increased emissions could lead to exceedances of the EU limits also (Environmental Protection Agency, 2018). Therefore development of mitigation measures to reduce air pollution is critical to achieve revised limits and reduce health impacts. Significant reductions in air pollution can be achieved by targeting the transport sector, the energy sector and improving the energy efficiency of residential properties (World Health Organisation, 2021).

1.2. Research Objectives

The overall aim of the research described in this project is to develop a model which can be used to estimate concentrations at various locations, to evaluate the impacts of various mitigation measures and is of interest to industry / researchers in the development of future policies. The research objectives of this project are as follows:

1. To develop an in-depth understanding on NO_2 in relation to pollution sources and pollutant modelling techniques by carrying out a comprehensive review of existing research. The literature review will identify the best pollutant modelling approaches by analysing results achieved internationally. Identifying NO_2 pollution sources will identify the most important sources and the importance of accounting for these sources within the selected pollutant modelling approach. A review of literature on links between pollutant exposure and health effects will emphasise the importance of reducing pollution levels by implementing mitigation measures.
2. To develop a model which has the capability of identifying environmental, meteorological and traffic related conditions which result in increased concentrations of NO_2 at various locations in Ireland. This objective includes expanding the traffic related parameter within the model to account for vehicle fleet breakdown on each of the routes surrounding a study location. This model will be able to estimate NO_2 concentrations and estimate changes in concentrations due to the implementation of mitigation measures such as adjustments in the vehicle fleet composition.
3. To implement the above model in a format / software which is easily accessible and which reduces the amount of data processing and time required of future modellers to estimate NO_2 concentrations. This objective includes the selection of the software which would be used to develop the model, processing of data which would be contained within the background of the model to reduce calculation times for future modellers and formatting of model to reduce input errors and simplify calculation process.
4. To evaluate the capability of the model to calculate changes in ambient NO_2 concentrations for unique scenarios and determine the effect of individual variable changes on concentration changes. This evaluation includes characterising the meteorological, environmental and traffic conditions during the 1st COVID lockdown period and comparing modelled NO_2 concentrations with measured concentrations at various locations during this period. Based on the performance of

the model in this scenario, the potential NO_2 reductions that can be achieved by each variable will be estimated.

5. To develop mitigation strategies to reduce NO_2 levels in Ireland by analysing strategies introduced in other countries and determining which strategies are the most suitable for implementation in Ireland. This investigation uses the model to evaluate selected mitigation measures which target one or a number of variables within the model (i.e. Inverse Distance Weighted Vehicle Kilometres Travelled, Road Density, Commercial Properties, Meteorological, Land Use and Vehicle Fleet Breakdown). This involves collection and processing of data on each of the variables listed above for each of the measures and determining the changes in NO_2 concentrations due to the implementation of mitigation measures.

1.3. Thesis Layout

This section introduces the layout of the thesis and provides details of the content in each of the chapters. Chapter 2 covers the review of literature which is relevant to NO_2 modelling and mitigation. The review covered topics such as the air monitoring network in Ireland, the air quality in Ireland with respect to NO_2, main sources of NO_X, transport in Ireland, vehicle emission standards, health impacts of NO_2 exposure and pollutant modelling approaches.

Chapter 3 introduces the methodology behind the original Wind Sector Land Use Regression (WS-LUR) model development and identifies the alteration made in this research project to the original WS-LUR model. The alteration introduces an emission weighting based on vehicle types, fuel types and Euro Classification to further strengthen the correlation of the model with local measured concentrations by providing a better representation of the type of traffic on routes surrounding a study location (e.g. high levels of Heavy Duty Vehicles (HDVs), mainly cars, public transport routes) and to enable the analysis of mitigation strategies that reduce emissions from specific classes of vehicle. The sources of data and methodology of data processing for each of the predictor variables within the model are also described in this chapter and the outputs of the data processing form the data for the pre-set analysis options stored within the model and later support the analysis of NO_2 concentrations between 2016 and 2018.

The layout of the WS-LUR model developed within Excel is introduced in Chapter 4. A step-by-step process which is useful for future use of the model is presented for both analysis methods (pre-set or manual entry). All sections / spreadsheets within the model are introduced in this chapter and details of the key information required to calculate the NO_2 concentration are highlighted. A number of modeller friendly functions which were included in the model to reduce errors are introduced. The process of calculating the NO_2 contribution from a wind directional sector or an individual predictor variable is demonstrated.

Chapter 5 presents the results and a discussion of the emission weighting calculations required in the new model, and the results and a discussion of the model validation (including a contemporary validation of the original model). Model validation is based on comparisons of measured and modelled concentration results. An analysis (methodology, data sources, results and discussion) of a unique scenario / environment (1^{st} COVID lockdown period) is also described in this chapter and a further validation was carried out to determine the accuracy of the model under these unique conditions. This validation examined a number of factors, including:

- Comparison of modelled and measured concentrations
- Comparison of measured differences and modelled differences between the pre-COVID and COVID scenarios
- An analysis of changes in concentration due to individual predictor variables.

Chapter 6 introduces a number of NO_2 mitigation measures that were analysed using the WS-LUR model. A background and literature review is provided for each mitigation measure, which identifies a number of reasons for selecting the mitigation measures and why the measures would be a positive approach for dealing with air quality issues in Ireland. The data sources, methodology, results and discussion of each of the mitigation measures are also described in this chapter.

Chapter 7 provides a discussion on the research which includes describing the main contributions and findings, the limitations of the research and areas of future research. Chapter 8 concludes the thesis by summarising the research.

1.4. Flow Diagram of Research

The primary objective of this research was to develop an LUR model capable of accounting for the vehicle fleet breakdown on routes surrounding a study location that can accurately estimate NO_2 concentrations. This model would then be used to examine mitigation measures which can target traffic, environmental and meteorological variables and determine the resultant changes in NO_2 concentrations. Figure 1.4 shows a flow diagram of the steps taken within the research to develop and validate the model and analyse a number of mitigation measures. A significant amount of data processing was required in advance of each analysis in the research and these steps are identified in the flow diagram. Additional literature review was carried out in advance of the mitigation measure analysis to determine the potential reduction in NO_2 that could be expected from each measure as shown in Figure 1.4.

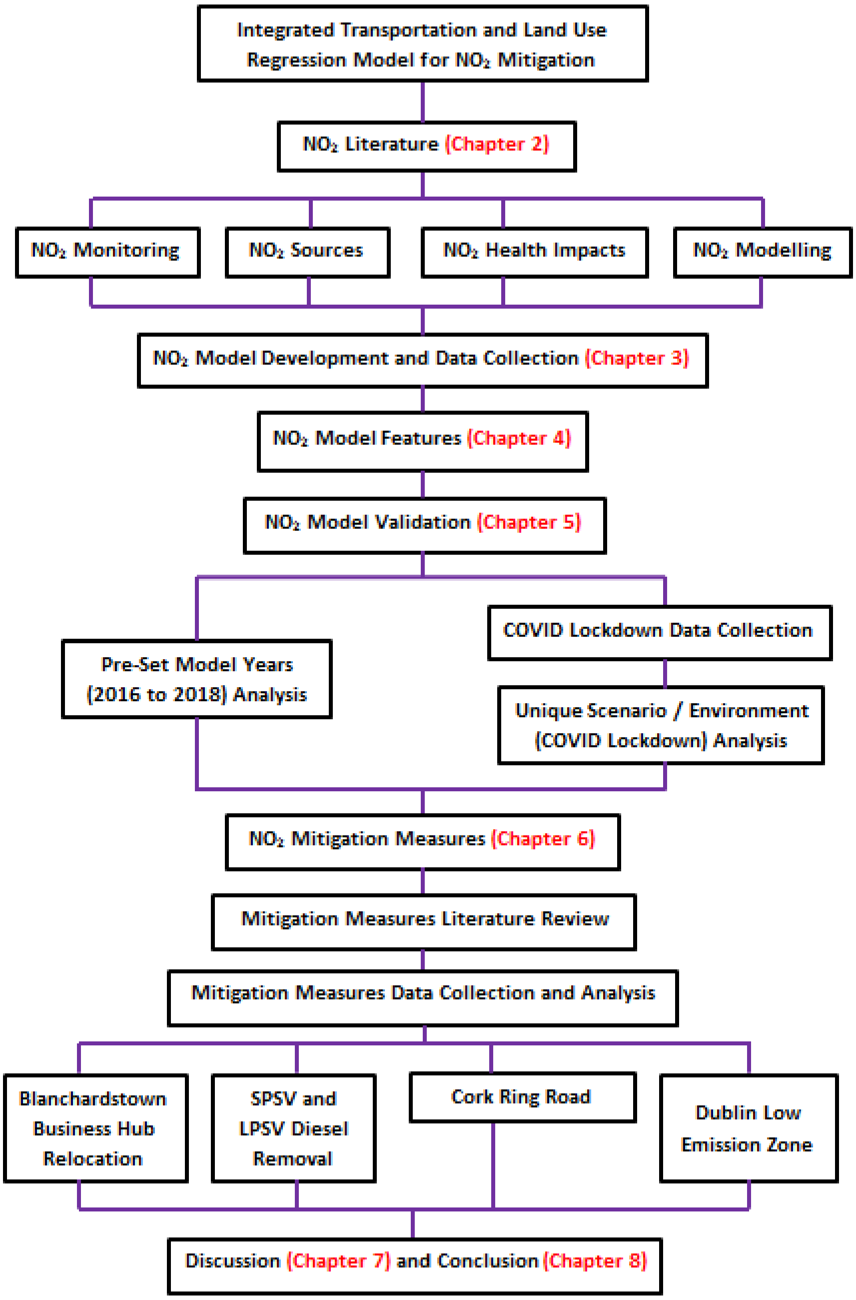


Figure 1.4: Flow Diagram of Research

2. Literature Review

In this chapter, a review of literature on topics related to air pollution and air pollution modelling is covered. These topics include a description of the air quality monitoring network in Ireland, an introduction to Nitrogen Dioxide (NO_2) pollution and sources of the pollutant, the air quality in Ireland with respect to NO_2, an insight into the transport sector in Ireland which is the main source of NO_2, an introduction to the Euro Emission Standards which aim to reduce the pollution from the vehicle fleet, a review of literature linking NO_2 exposure and other pollutants with health effects and a review of modelling approaches which are commonly used to estimate pollutant concentrations.

2.1. Environmental Protection Agency (EPA) Air Quality Monitoring Network

The EPA air quality monitoring network consists of 62 monitoring sites throughout the country, as of March 2022, and 19 of these sites are located in County Dublin, as shown in Figure 2.1 (Environmental Protection Agency, 2019). Another 34 sites were used to monitor various pollutants but publicly available monitoring data at these locations have ceased. The National Ambient Air Quality Monitoring Programme was launched in 2017 to expand the existing monitoring network and to provide more local information on different environments in built-up and rural areas and is planned to be completed by the end of 2022 (Environmental Protection Agency, 2017). Further monitoring at new locations will provide a clearer image of the standard of air quality in Ireland and also confirm if Ireland is in compliance with the EU standards (European Union, 2008) and WHO guidelines (World Health Organisation, 2006) described in Section 2.2, which will also assist in highlighting potential problem locations in the country that may require mitigation plans to limit or reduce the air pollution. A total of 30 current monitoring stations collect data relating to oxides of nitrogen.

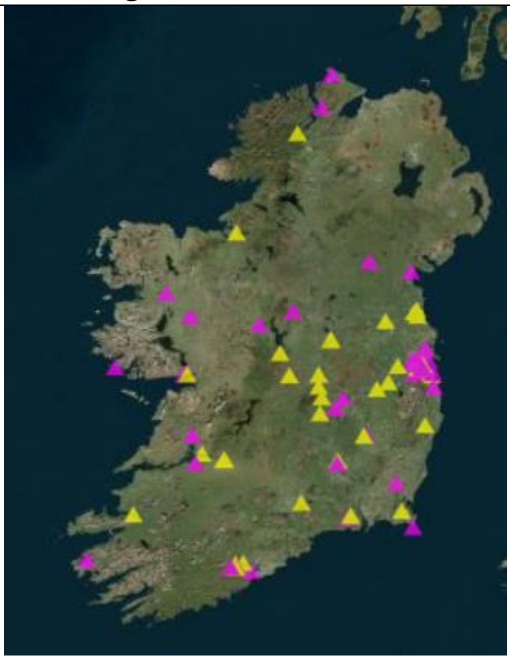


Figure 2.1: National Air Quality Monitoring Network Current Sites (Purple) and Past Sites (Yellow) (Environmental Protection Agency, 2019)

The expansion of the network as part of the programme is seen to be a positive approach in illustrating local air quality conditions to the public and encouraging people to think about improving air quality in their everyday decisions, such as modes of transport or home heating. Information from the monitoring stations is transferred to an Air Quality Index Map (Environmental Protection Agency, 2019) which divides the country into regions of small towns / large towns, Cork City and Dublin County. The remaining area of the country, not covered by those regions, is split between the rural west and rural east regions, with an index rating assigned to each region. Real-time information from the monitoring stations is then used to categorise the air quality as good, fair, poor or very poor in each of the regions as shown in Figure 2.2. Separate recommendations are then provided for the general population and at-risk individuals (children, elderly people and adults with respiratory or cardiovascular issues) in relation to outdoor activities based on the quality categories.

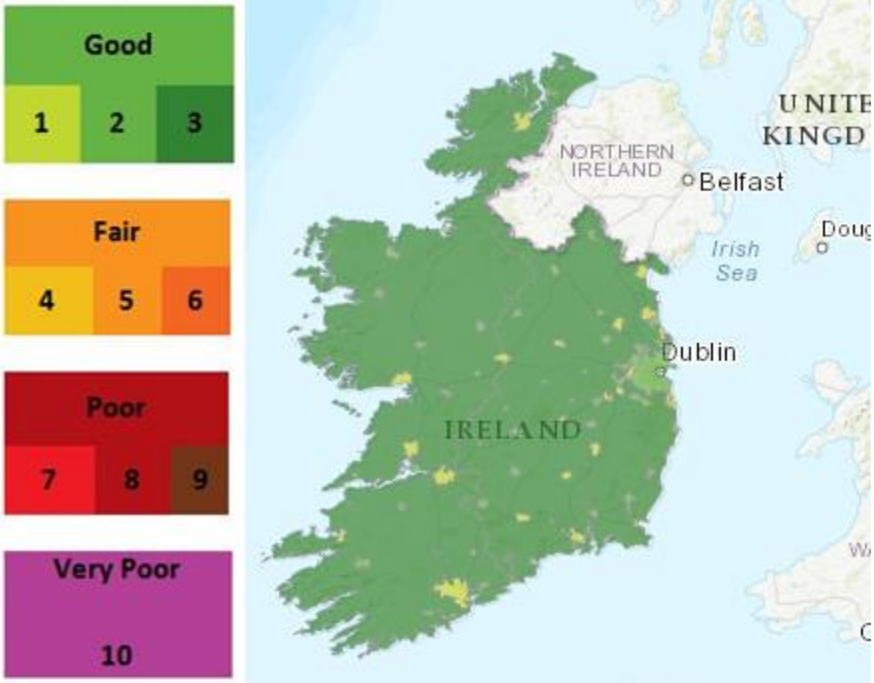


Figure 2.2: EPA Air Quality Index for Health Map (Environmental Protection Agency, 2019)

2.2. Nitrogen Dioxide

Nitrogen Dioxide (NO_2) can be naturally formed by lightning which creates a very high temperature environment resulting in the oxygen and nitrogen molecules in the air to react to form Nitric Oxide (NO) which then reacts with more oxygen molecules to form NO_2 (Chemistry Libre Texts, 2018), the chemical equation of which is shown in Equations 2.1 and 2.2 below.

$$N_2 + O_2 \xrightarrow{high\ temperature\ environment} 2\,NO$$ **Eqn. 2.1: Nitric Oxide Formation**

$$2\,NO + O_2 \rightarrow 2\,NO_2$$ **Eqn. 2.2: Nitrogen Dioxide Formation**

The main source of Nitric Oxide (NO) and NO_2 in Ireland since 1990 has been the transport sector which contributes to over 50% of the total NO_X emitted every year, as shown in Figure 2.3. Statistics relating to transport in Ireland are discussed in Section 2.4 below. As of 2014, the total NO_X emissions were still above the National Emission Ceilings Directive (2016/2284/EU) target (European Union, 2016), which is a 49% decrease in NO_X by the year 2020 in comparison with 2005. An additional target of a 69% decrease in comparison to the 2005 total has been set for every year from 2030 onwards. As shown in Figure 2.3, the majority of the reduction in NO_X to date, is attributable to improvements at power stations which have introduced a number of key measures to reduce emissions such as low NO_X burners which control the proportion of fuel to air in the combustion process and selective catalytic reduction which creates a chemical reaction with ammonia (NH_3) to split NO_2 into Nitrogen molecules and water (European Environment Agency, 2007).

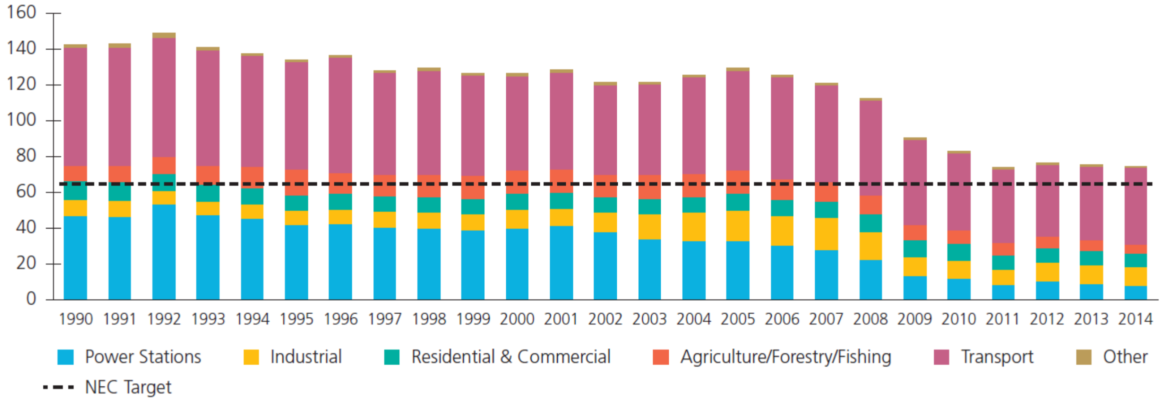


Figure 2.3: Total NOx Emissions in Ireland 1990-2014 (Environmental Protection Agency, 2016)

The World Health Organisation's Guidelines (World Health Organisation, 2006) and the European Union's Directive on Ambient Air Quality and Cleaner Air for Europe (2008/50/EC) (European Union, 2008) have set out short-term and long-term concentration limits for numerous air pollutants including NO_2 as research has confirmed that excessive exposure to the gas can have serious impacts on health, as shown in Section 2.5. The short-term limit (1-hour mean) of 200 $\mu g/m^3$ was set out after various animal and human studies concluded that concentrations in excess of this limit are considered toxic and have a significant impact on health. (World Health Organization, 2005). This concentration level is accepted in the EU Directive as long as it does not exceed this limit more than 18 times a year at any individual monitoring station. The long-term limit (annual mean) set by both the World Health Organisation and Directive 2008/50/EC was 40 $\mu g/m^3$ prior to September 2021 based on results from studies carried out on mixtures of air pollutants containing NO_2, which showed that people experienced health effects with increasing NO_2 concentrations (World Health Organization, 2005; European Union, 2008). The World Health Organisation revised this limit to 10 $\mu g/m^3$ after substantial evidence was available linking NO_2 exposure above these levels to numerous health effects (World Health Organisation, 2021). In accordance with the EU Directive, an alert threshold exists where members of the public must be notified if concentration levels of NO_2 exceed 400 $\mu g/m^3$ for more than 3 consecutive hours. The EU Directive also sets out thresholds for both the annual mean and hourly concentrations to protect human health (European Union, 2008).

The upper assessment threshold for the hourly limit is set at 70% (140 µg/m^3) of the limit concentration and the lower assessment threshold is set at 50% (100 µg/m^3). The annual mean upper and lower assessment thresholds are set at 80% (32 µg/m^3) and 65% (26 µg/m^3) respectively.

Since 2000, the annual mean limit value was exceeded on 4 occasions in Ireland, all of which occurred prior to 2010, the year in which the limit was implemented. All four occurred at Dublin City monitoring stations, as shown in Table 2.1. In response to the exceedance in 2009, all of the Dublin County Councils (Dublin City, South Dublin, Fingal County and Dún Laoghaire Rathdown County) cooperated to develop an Air Quality Management Plan to tackle the issue of increasing air pollution in the county (Dublin City Council, South Dublin County Council, Fingal County Council, Dún Laoghaire Rathdown County Council, 2009) and the Smarter Travel Policy for Sustainable Transport report was published to identify objectives in reducing transport related air pollution in Ireland from 2009 – 2020 (Department of Transport, 2009).

Table 2.1: WHO Guideline and EU Directive Annual Mean Exceedances in Ireland 2000-2017

Year	Locations of Annual Mean Limit Exceedances (>40 µg/m^3)	Source
2009	Winetavern Street	(Environmental Protection Agency, 2010)
2001	Coleraine Street	(Environmental Protection Agency, 2002)
2000	Coleraine Street, Pearse Street	(Environmental Protection Agency, 2001)

The lower assessment threshold of 100 µg/m^3 has been breached more than 18 times in multiple years since 2010 at both the Winetavern Street and Blanchardstown monitoring stations. The EU hourly guideline has not been exceeded at any location since its implementation in 2010, but in 2001, records showed that concentrations of 200 µg/m^3 or greater were achieved 178 times at Wood Quay in Dublin City. Concentration levels in excess of 200 µg/m^3 were recorded at a number of locations since 2000. The majority of these exceedances were located in County Dublin, as shown in Table 2.2, and most of which occurred during the morning and evening heavy traffic periods. No breaches of the limit value were recorded in the years 2004, 2006, 2007, 2010 and 2015.

Table 2.2: WHO Guideline Hourly Limit Exceedances in Ireland 2000-2017

Year	Hours > 200 µg/m^3 (Location)	Source
2017	1 (Blanchardstown)	(Environmental Protection Agency, 2018)
2016	1 (Swords)	(Environmental Protection Agency, 2017)
2014	2 (Blanchardstown)	(Environmental Protection Agency, 2015)
	5 (Swords)	
2013	1 (Swords)	(Environmental Protection Agency, 2014)
2012	1 (Swords)	(Environmental Protection Agency, 2013)
2011	1 (Blanchardstown)	(Environmental Protection Agency, 2012)
	1 (Swords)	
	1 (Ringsend)	
2009	6 (Blanchardstown)	(Environmental Protection Agency, 2010)
	6 (Swords)	
	1 (Ballyfermot)	
2008	1 (Blanchardstown)	(Environmental Protection Agency, 2009)
	1 (Navan)	
2005	1 (Winetavern Street)	(Environmental Protection Agency, 2006)
2003	1 (Winetavern Street)	(Environmental Protection Agency, 2005)
	5 (Ballyfermot)	
	1 (Crumlin)	
	2 (Sligo)	
	3 (Athlone)	
2002	15 (Winetavern Street)	(Environmental Protection Agency, 2002)
	3 (Old Station Road, Cork)	
2001	178 (Wood Quay, Dublin)	(Environmental Protection Agency, 2002)
	1 (Coleraine Street)	
2000	1 (Coleraine Street)	(Environmental Protection Agency, 2001)
	3 (Rathmines)	
	2 (Limerick)	

Dispersion modelling of NO_2 and diffusion tube sampling carried out by the Environmental Protection Agency in 2016 and 2017 have indicated that a number of locations in Dublin City, which previously had annual mean NO_2 levels close to the limit value may now be exceeding the limit (Environmental Protection Agency, 2019). It was projected that the most heavily polluted areas were streets in the city centre, at both sides of the Dublin Port Tunnel and along the M50 motorway (Environmental Protection Agency, 2019).

A number of previous research projects completed under the ERTDI and STRIVE programmes have investigated the levels and distribution of NO_2 concentrations in Ireland, including methods of assessment. Broderick et al. (2006) validated emissions and dispersion models for predicting roadside concentrations of pollutants in Ireland, including NO_2. Kelly (2006) and Kelly (2011) applied the RAINS and GAINS model in Ireland, which include oxides of nitrogen amongst the pollutants considered, as policy support tools. Morrin et al. (2015) developed improved inventories for NOx emissions from transport and small scale combustion installations in Ireland. Donnelly et al. (2019) developed an air quality forecast model for Ireland compatible with the Air Quality Index for Health that included the capability to forecast ambient NO_2 concentrations. The forecast model was further developed to produce national maps of annual and short-term NO_2 concentrations using land use regression.

2.3. Euro Emission Standards

Table 2.3 shows limit values for air pollution by emissions from motor vehicles as set out in the European standards for each Euro vehicle class. The first European standard for vehicle emissions was introduced in 1970 but it was not until 1992 when a standard for vehicle emissions, applicable to all of the European countries, was produced, known as Euro 1 (RAC, 2019). The Euro 1 standard introduced in July 1992 set out to reduce carbon monoxide (CO) emissions from vehicles and this reduction was to be achieved by making the change to unleaded petrol fuelled vehicles and the requirement to install catalytic converters in petrol cars (RAC, 2019).

The Euro 2 standards focused on assigning separate limits for petrol and diesel vehicles whilst the Euro 3 revision introduced individual limit values for hydrocarbons (HC) and NO_X which were previously subject to a combined limit. All emission limits for both petrol and diesel vehicles experienced major reductions, except CO emissions from petrol engines, which were reduced initially in the Euro 2 standard from 2.72 g/km to 2.2 g/km but were then increased to 2.3 g/km in the Euro 3 standard.

The introduction of the Euro 4 and 5 standards focused on considerably reducing NO_X and Particulate Matter (PM) in diesel vehicle emissions with NO_X limits reduced from 0.15g/km to 0.06 g/km and from 0.5 g/km to 0.18 g/km for petrol- and diesel-engine vehicles respectively. The PM limit for diesel powered cars was reduced from 0.05 g/km to 0.005 g/km and the same limit value was introduced for the first time for direct injection petrol powered cars in the Euro 5 revision. Petrol vehicle standards experienced major changes over the two revisions also, with all emission limits reduced by 50% or more. The Euro 5 revision made it necessary to install Diesel Particulate Filters (DPFs) on all diesel vehicles to achieve the reduced limit values (RAC, 2019). However, the installation of DPFs to reduce PM has counteracted efforts to reduce NO_X emissions with studies showing that NO_X emissions increased by approximately 30% in comparison to vehicles without DPFs (Ko et al., 2019). The update for Euro 5 class limits also made minor reductions to the Total Hydrocarbons and NO_X emission limits to restrict the potential negative impact the DPFs could have on these emissions and introduced a limit on the number of particles to accompany the particle weight limit which had been in effect since the Euro 1 standards, as shown in Table 2.3.

The Euro 6 standards focused on the reduction of NO_X emissions from motor vehicles as more research studies linked the pollutant with respiratory health problems (RAC, 2019).

This update resulted in car manufacturers introducing the Selective Catalytic Reduction (SCR) process in their vehicles to comply with the new limits for NO_X. SCR adds a liquid reductant to a catalyst within the exhaust of diesel vehicles, which then reacts with the NO_X, transforming it into water and nitrogen (Manufacturers of Emission Controls Association, 2007). The SCR process can reduce NO_X emissions by approximately 60% and NO_2 emissions by approximately 15% in comparison to the Lean NO_X Trap (LNT) diesel vehicles (Carslaw et al., 2019). The LNT process begins by oxidising the Nitric Oxide (NO) into NO_2 with the use of a catalyst, which is then stored until the engine is run in a rich (high fuel-to-air ratio) manner and this reduces the NO_2 to Nitrogen (N_2) (Manufacturers of Emission Controls Association, 2007). The LNT procedure is being retained by a number of vehicle manufacturers, mainly for smaller engine sizes, less than 2 litres, despite the major reductions in emissions as they can achieve the limit values set out in the Euro 6 standard (O'Driscoll et al., 2016; The International Council on Clean Transportation, 2016).

Table 2.3: Euro Emission Standards Vehicle Classification (European Union, 2012; European Union, 2007; European Union, 1998; European Union, 1994; European Union, 1991)

Euro Standard New Vehicle Approval Date (New Vehicle Registration Date)	Emission	Petrol Limit	Diesel Limit
Euro 1	CO	2.72 g / km	2.72 g / km
July 1992	HC + NO_X	0.97 g / km	0.97 g / km
(January 1993)	PM (Particle Weight Limit)	-	0.14 g / km
Euro 2	CO	2.2 g / km	1.0 g / km
January 1996	HC + NO_X	0.5 g / km	0.7 g / km
(January 1997)	PM (Particle Weight Limit)	-	0.08 g / km
	CO	2.3 g / km	0.64 g / km
Euro 3	HC	0.2 g / km	-
January 2000	HC + NO_X	-	0.56 g / km
(January 2001)	NO_X	0.15 g / km	0.5 g / km
	PM (Particle Weight Limit)	-	0.05 g / km
	CO	1.0 g / km	0.5 g / km
Euro 4	HC	0.1 g / km	-
January 2005	HC + NO_X	-	0.3 g / km
(January 2006)	NO_X	0.08 g / km	0.25 g / km
	PM (Particle Weight Limit)	-	0.025 g / km
	CO	1.0 g / km	0.5 g / km
Euro 5	THC / NMHC	0.1 g / km (THC) 0.068 g / km (NMHC)	-
September 2009	THC + NO_X	-	0.23 g / km
(January 2011)	NO_X	0.06 g / km	0.18 g / km
	PM (Particle Weight Limit)	0.005 g / km (direct injections only)	0.005 g / km
	PM (Particle Number Limit)	-	6.0×10^{11} km
	CO	1.0 g / km	0.5 g / km
Euro 6	THC / NMHC	0.1 g / km (THC) 0.068 g / km (NMHC)	-
September 2014	THC + NO_X	-	0.17 g / km
(September 2015)	NO_X	0.06 g / km	0.08 g / km
	PM (Particle Weight Limit)	0.0045 g / km (direct injections only)	0.0045 g / km
	PM (Particle Number Limit)	6.0×10^{11} km (direct injections only)	6.0×10^{11} km

A recent study on the direct emission of NO_2 and NO_X from vehicles shows that NO_2 emissions reduce with increasing vehicle mileage, which is an important factor in the mapping of emissions based on vehicle age, as using the emission values achieved by the vehicle when new could greatly overestimate the pollutant (Carslaw et al., 2019) but this could be attributed to the reduction in the efficiency of DPFs introduced as part of the Euro 5 revision, which focused on reducing PM emissions. The study also found that NO_2 emissions from Euro 3 vehicles increased initially and peaked in the 100 000 to 150 000 kilometre range, as shown in Figure 2.4. The Euro 6 vehicle remains the best option with respect to NO_2 emissions, as it is the only vehicle class which emits less than 3 grams of NO_2 per kilogram of fuel, as shown in Figure 2.4. The proportion of NO_X, which is $NO_{2,}$ is reported to be decreasing in most of the European cities based on the comparison of the 2005-2010 period and 2010-2015, which would align with the results of Carslaw et. al. (2019) but this was not the case in Dublin City as the NO_2: NO_X ratio increased considerably (Grange et al., 2017).

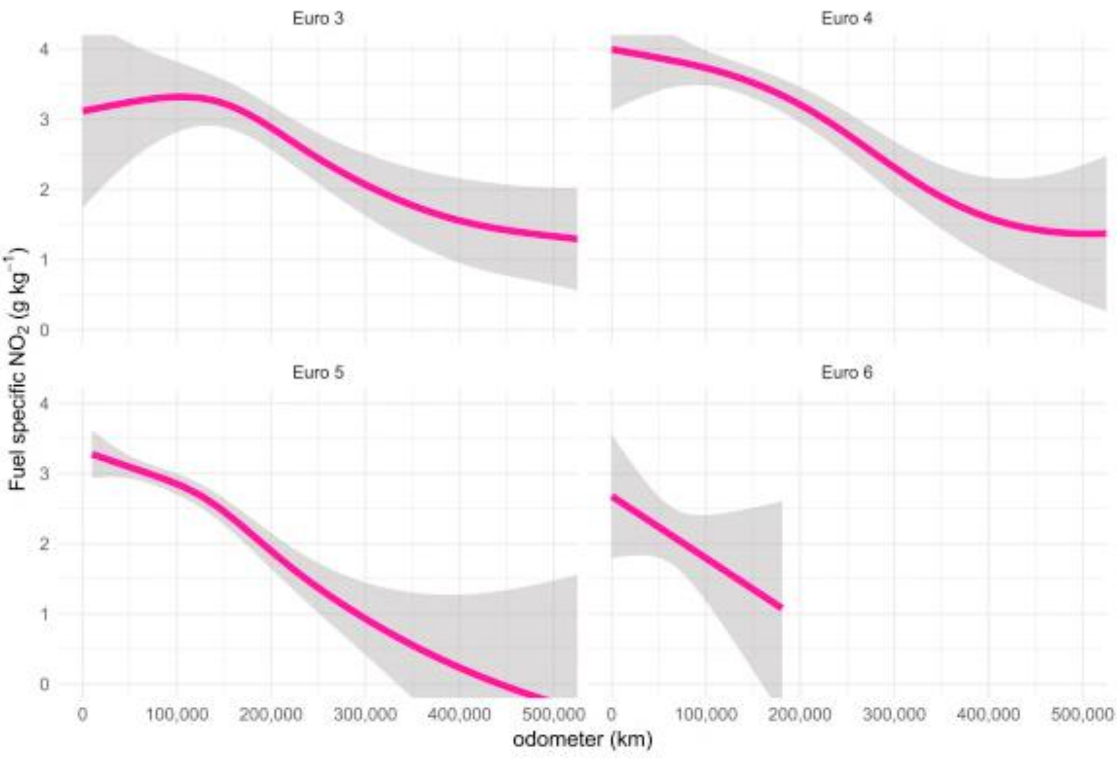


Figure 2.4: Euro Class NO_2 Emissions with Increasing Mileage (Carslaw et al., 2019)

2.4. Transport in Ireland

The number of licenced vehicles in Ireland has increased from 922 484 to 2.68 million between 1987 and 2017. Between 2008 and 2012, the overall number of vehicles reduced year on year but this was mainly due to the reduction in the number of licenced private cars, as all other forms of vehicles remained constant or had very minor increases in numbers, as shown in Figure 2.5. The upward trend in licenced private cars experienced prior to 2008 continued from 2012 onwards. Licencing of new vehicles in Ireland experienced reduced numbers between 2009 and 2013, which is a 1 year lag in comparison to the pattern of the total vehicle numbers (Department of Transport, Tourism and Sport, 2018). Therefore the increase in the total number of vehicles in 2013 could only be due to second hand vehicles being retained on the roads and used vehicle imports, which had increased by 25.4% that year in comparison to 2012 (Motorstats, 2019).

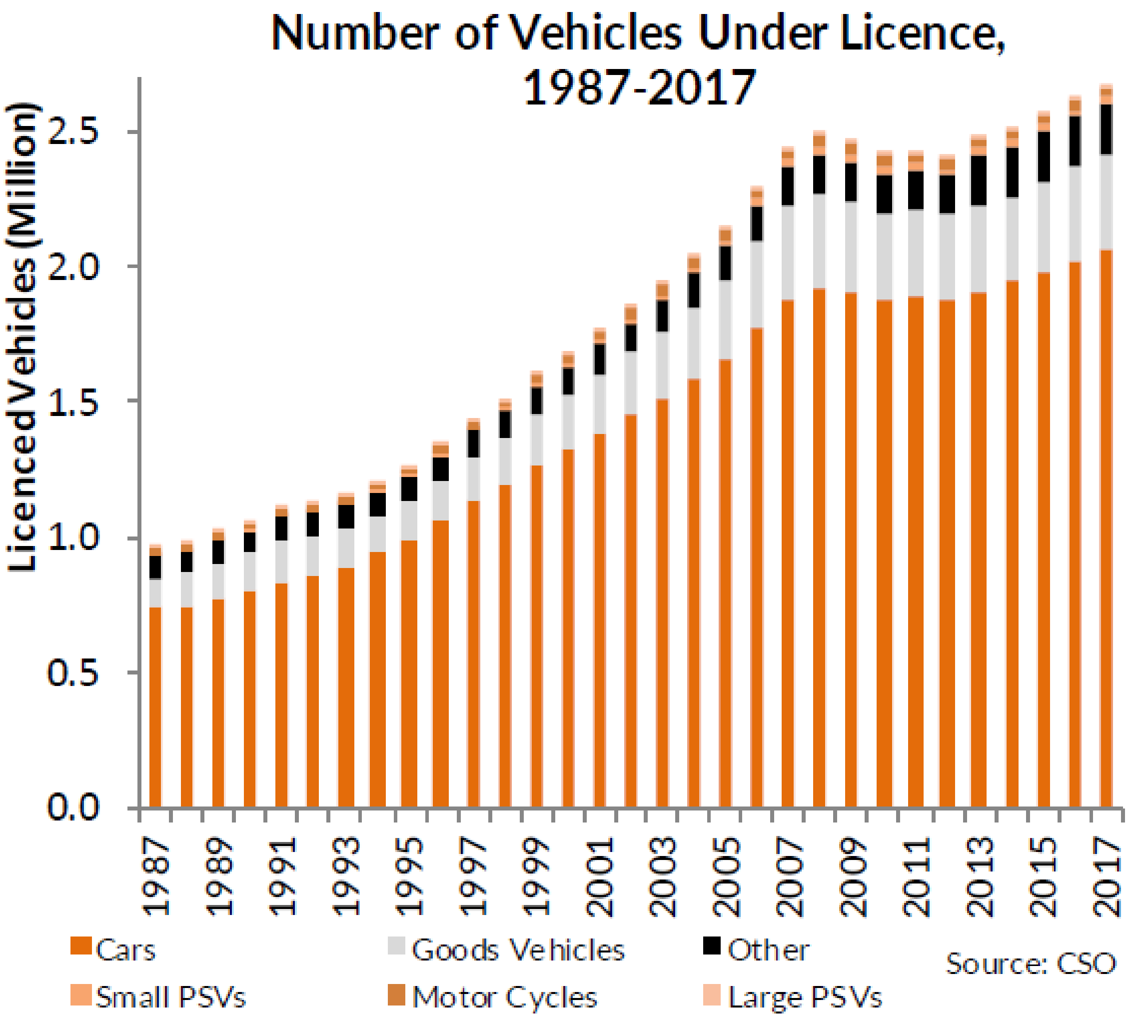


Figure 2.5: Number of Vehicles Under Licence in Ireland 1987-2017 (Department of Transport, Tourism and Sport, 2018)

2.4.1. Commuting and Work Based Travel

The transport sector is responsible for the majority of NOx emissions in Ireland (Figure 2.3), and these emissions lead to increased NO_2 concentrations in urban areas where population exposure is greatest. Primary NO_2 emissions from motor vehicles are of concern because in the EU most exceedances of the 40 µg/m^3 annual mean limit value occur in the near road environment (Carslaw et al., 2019). The car is the main mode of transport for commuting to work in Ireland and has increased from 55% of total work population journeys in 1986 to 65.6% (1.23 million people) in 2016, as shown in Figure 2.6 (Department of Transport, Tourism and Sport, 2018). Walking to work has seen a gradual decrease in popularity between 2006 and 2016 to 9.3% but cycling has increased to 3% and public transport has remained at approximately 9% in the same time period. When including journeys for leisure purposes, the preference for the car is further increased at 74.3% of the journeys in 2016 and public transport, walking and cycling account for 21.8% of the journeys (5.5% public transport, 16.3% walking and cycling) (Department of Transport, Tourism and Sport, 2018).

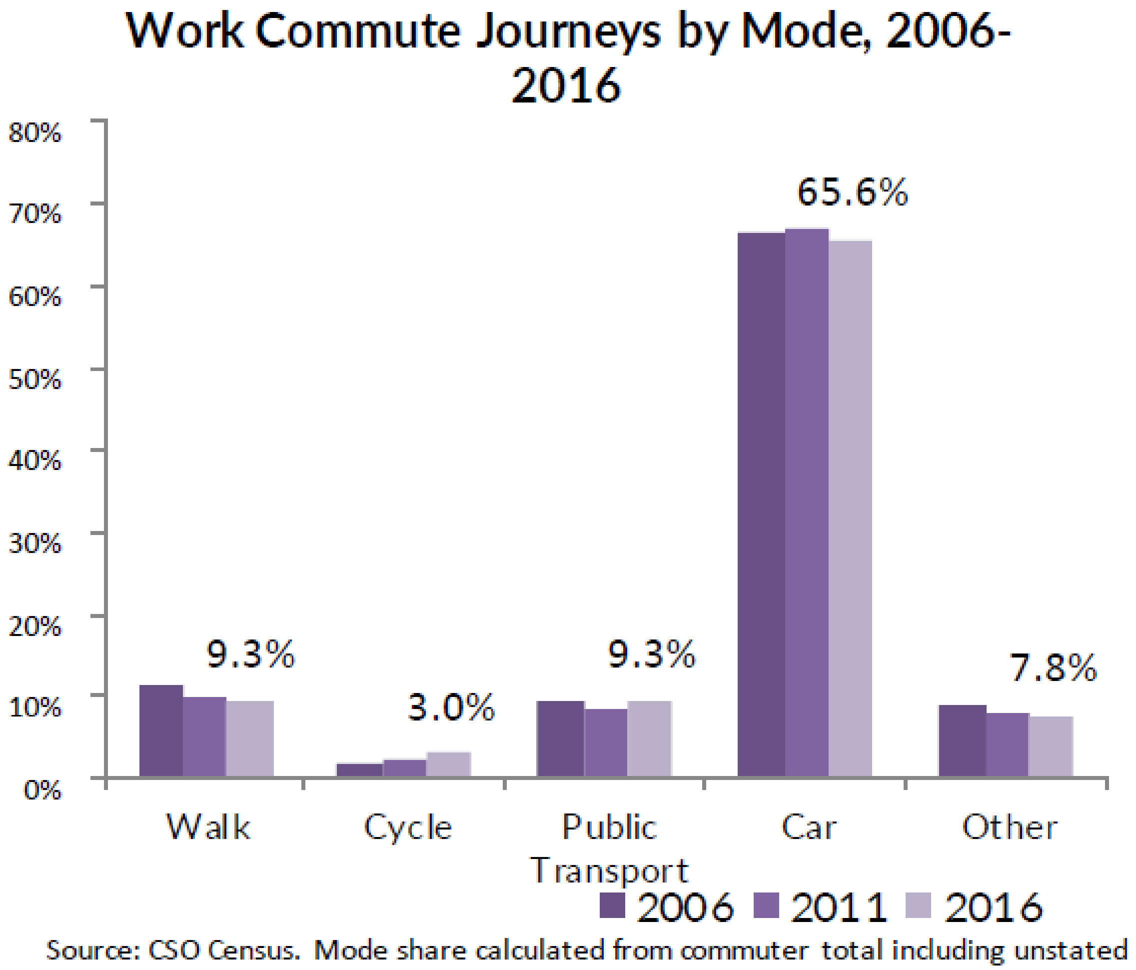


Figure 2.6: Work Commute Journeys by Mode 2006-2016 (Department of Transport, Tourism and Sport, 2018)

The average travel time to work has increased from 27.5 minutes in 2011 to 28.2 minutes in 2016 with Dublin City and County as well as surrounding counties and Galway County experiencing above average travel times suggesting travel distances have increased or there are traffic issues in these locations. Around 200 000 people had a travel time in excess of 1 hour in 2016 which is an increase of around 31% from the 2011 figures and this correlates with the increase in average travel time (Central Statistics Office, 2017). Car passenger kilometres accounted for 80.4% of the mode share in Ireland in 2015 which was below the European Union (EU) average of 83.1% of the mode share, as shown in Figure 2.7. Bus passenger kilometres made up 16.7% of the mode share in Ireland which is considerably greater than the EU average of 9.2% but train passenger kilometres are well below the average of 7.7% at 3% in 2015.

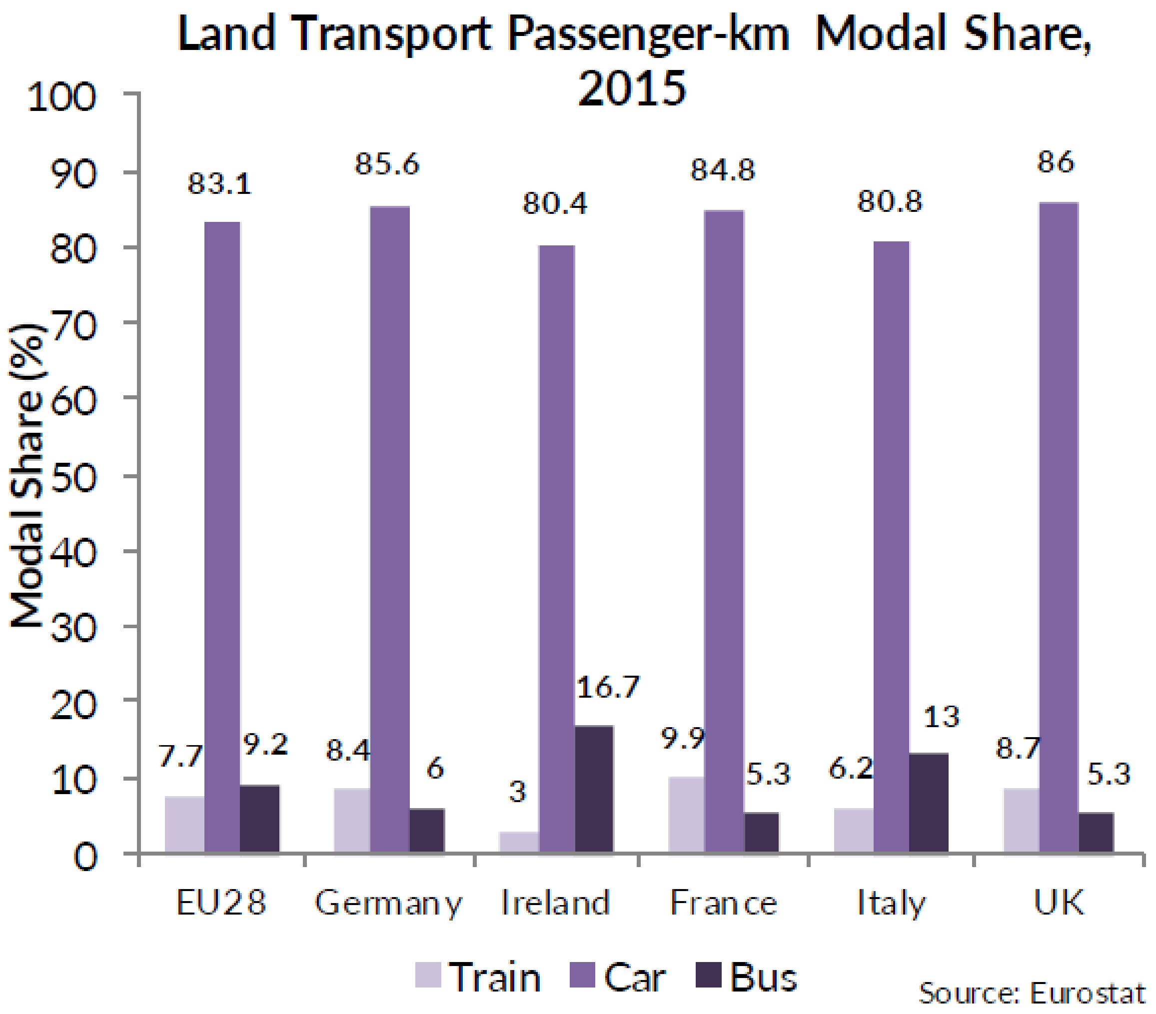


Figure 2.7: Land Transport Passenger Kilometres Modal Share 2015 (Department of Transport, Tourism and Sport, 2018)

The Central Statistics Office (Central Statistics Office, 2016) has identified that a large proportion of the working population in each of the five major cities in Ireland are commuting from regions outside of the city and suburbs, as shown in Table 2.4. The ratio of people working in their town of usual residence to people commuting to work is approximately 50:50 in both Limerick and Galway, whilst in Cork and Waterford this ratio is 59:41 and 54:46 respectively. The ratio for Dublin is significantly higher at 75:25 but the number of people commuting is also significantly greater than the other cities at 130 447 compared to the next largest population commuting into a city at 41 433 in Cork City (Central Statistics Office, 2016).

Table 2.4: Living and Working Population for the Five Major Cities in Ireland (Central Statistics Office, 2016)

City and Suburbs	Population Working in Town of Usual Residence	Population Commuting into Town for Work	Daytime Working Population
Cork	60 706 *(59%)*	41 433 *(41%)*	102 139
Dublin	382 002 *(75%)*	130 447 *(25%)*	512 449
Galway	22 271 *(50%)*	22 105 *(50%)*	44 376
Limerick	21 908 *(49%)*	22 716 *(51%)*	44 624
Waterford	13 101 *(54%)*	11 274 *(46%)*	24 375

The Central Statistics Office confirms that of the 211 591 households in Dublin City recorded in the 2016 Census, 90 793 households (43% of total households in Dublin City) were classified as rented accommodation (Central Statistics Office, 2016). This highlights that a substantial number of people accounted for in the figure of 382 002 working in their town of usual residence may be temporary residents and are living in the city / suburbs for work / education purposes. If their places of work or study were to be relocated, a proportion of this population may relocate to be more conveniently located for work / education.

Table 2.5 shows the top 10 counties for numbers commuting to Dublin City and its suburbs. Outside of County Dublin, County Kildare has the largest population of workers commuting to Dublin City and its suburbs at 28 121 (Central Statistics Office, 2016). A large population also travel from adjacent counties, such as Meath at 21 808, Wicklow at 19 008, South Dublin at 3 810, Laois at 2 937 and Offaly at 1 719. Counties such as Westmeath and Wexford also have considerable numbers commuting into Dublin City and suburbs at 2 519 and 2 490 respectively.

Table 2.5: Number of Commuters into Dublin City and Suburbs by County 2016 (Central Statistics Office, 2016)

Counties	No. of Commuters to Dublin City and Suburbs
Fingal	28 641 *(22%)*
Kildare	28 121 *(22%)*
Meath	21 808 *(17%)*
Wicklow	19 008 *(15%)*
Louth	4 900 *(4%)*
South Dublin	3 810 *(3%)*
Laois	2 937 *(2%)*
Westmeath	2 519 *(2%)*
Wexford	2 490 *(2%)*
Offaly	1 719 *(1%)*
Total Commuters from Outside of Dublin City and Suburbs	**130 447**

2.4.2. Transport Expenditure

Changes in travel demand and the associated NO_2 emissions are linked to economic growth. Ireland's Gross Domestic Product (GDP) per capita has been above the average of the countries within the Organization for Economic Cooperation and Development (OECD) since 1997, as shown in Figure 2.8 (OECD Data, 2019). Irish GDP per capita experienced a major increase in 2015 which led to Ireland becoming the second highest within the OECD, only behind Luxembourg. A similar trend cannot be seen in the investment in transport for Ireland as the share of the GDP spent on transport has reduced considerably from 0.8% in 2010 to approximately 0.3% in 2014, as shown in Figure 2.9 (Department of Transport, Tourism and Sport, 2018).

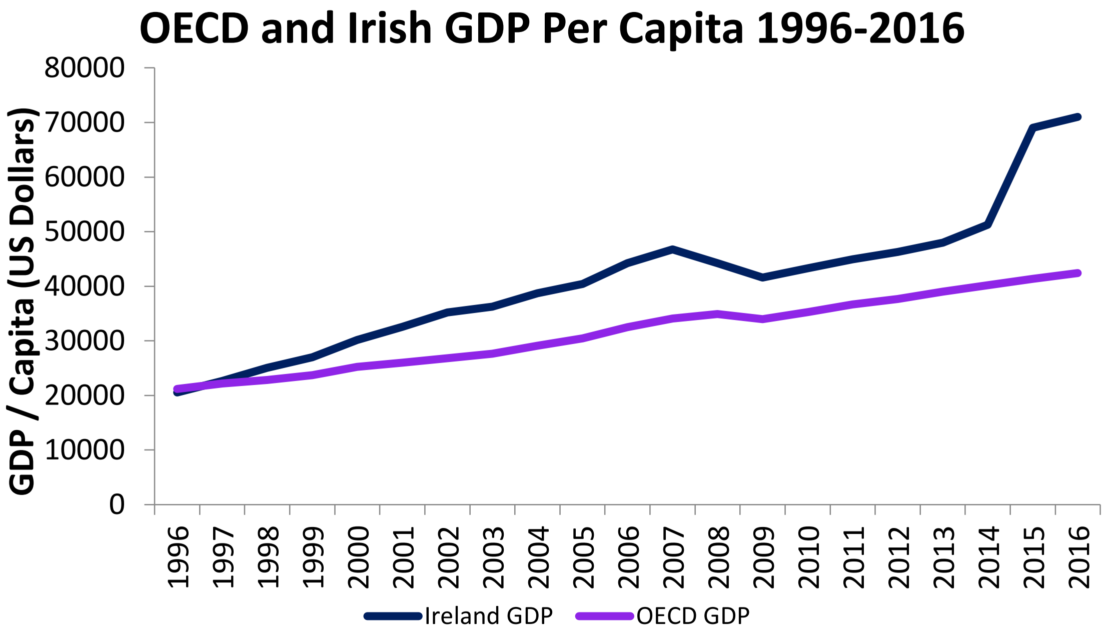


Figure 2.8: OECD Gross Domestic Product per Capita (OECD Data, 2019)

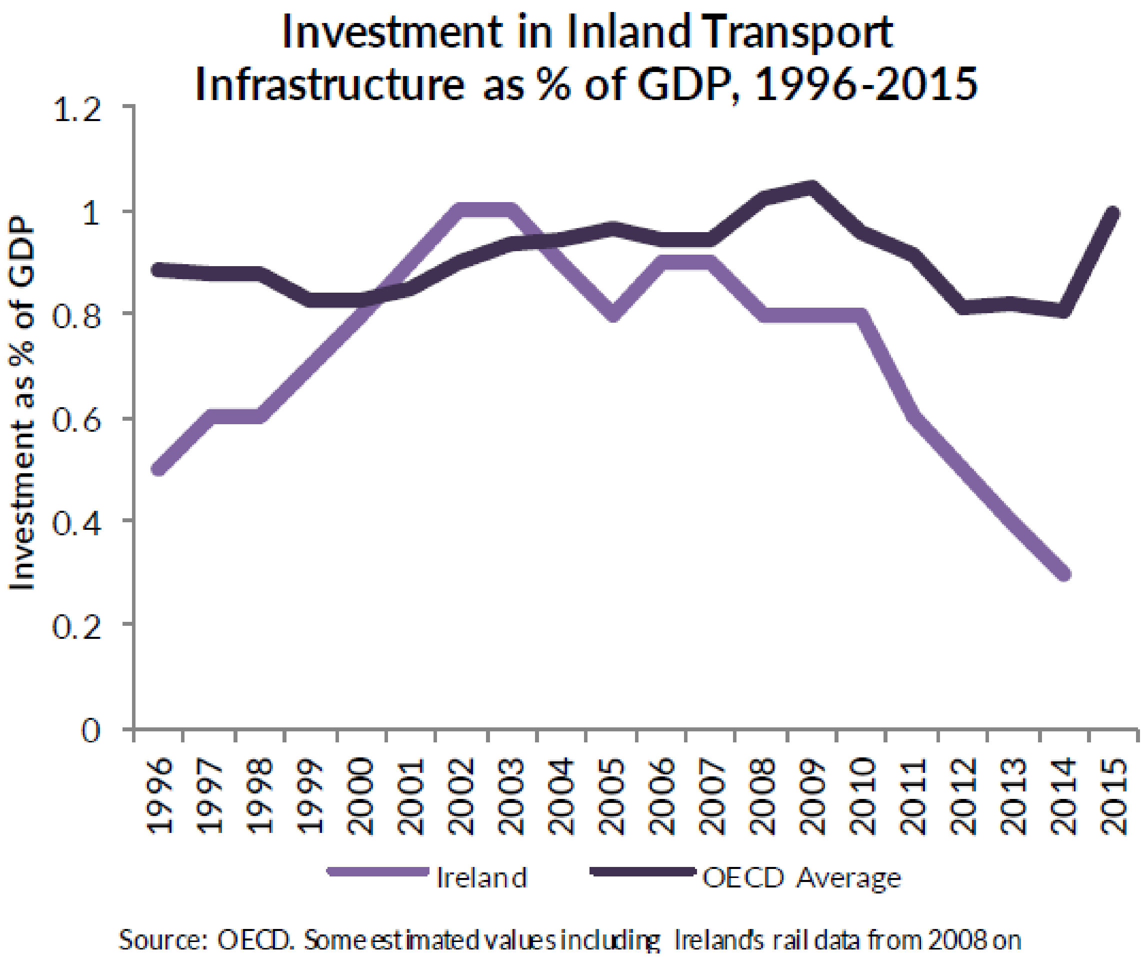


Figure 2.9: Investment in Transport as GDP % 1996-2015 (Department of Transport, Tourism and Sport, 2018)

2.4.3. Transport Network Development and Air Pollution Mitigation Measures

2.4.3.1. Construction Projects (Bypass and Relief Roads)

The United Kingdom had highlighted a number of locations where a bypass or relief road would provide positive results in reducing NO_2 concentrations and aim to reduce traffic travelling through built up areas such as projects in Llandeilo, Newtown and Ffairfach in Wales and the Gateway Mersey and Wakefield Eastern Relief Road (Department for Environment Food & Rural Affairs, 2015; Department for Environment Food & Rural Affairs and Department for Transport, 2017). These measures would aim to provide alternate routes for road network users reducing the congestion in a particular location as well as reducing the overall distance travelled by vehicles within built up areas or areas experiencing significant levels of pollution. This mitigation strategy was selected as it has the potential to change traffic flows across multiple routes within a greater urban area and reduce vehicle numbers travelling directly through a city centre.

In Ireland, the N6 Galway City Ring Road has been identified as a potential solution to relieve congestion during peak hours and to improve journey times within Galway City and County (N6 Galway City Transport Project, 2021); the current proposed alignment shown in Figure 2.10. In 2016, the population of Galway County was 179 400 and the population of Galway City was 78 700 (Central Statistics Office, 2017). The reliance on private cars is emphasised by the commuter numbers in Galway City and County published by the Central Statistics Office and shown in Section 2.4.1. A number of difficulties are typically highlighted when designing ring roads / bypasses such as space constraints for future development. In the case of the Galway City Ring Road, due to the location of the city there are limited options in terms of the alignments of the road between Galway Bay and Lough Corrib which are further compacted by numerous environmental constraints within the city and county such as National Heritage Areas and Special Areas of Conservation. There are currently four crossings over the River Corrib all of which pass directly through the city centre. Another crossing over the River Corrib is more than 40 km away from the city at the border between County Galway and County Mayo, as shown in Figure 2.11.

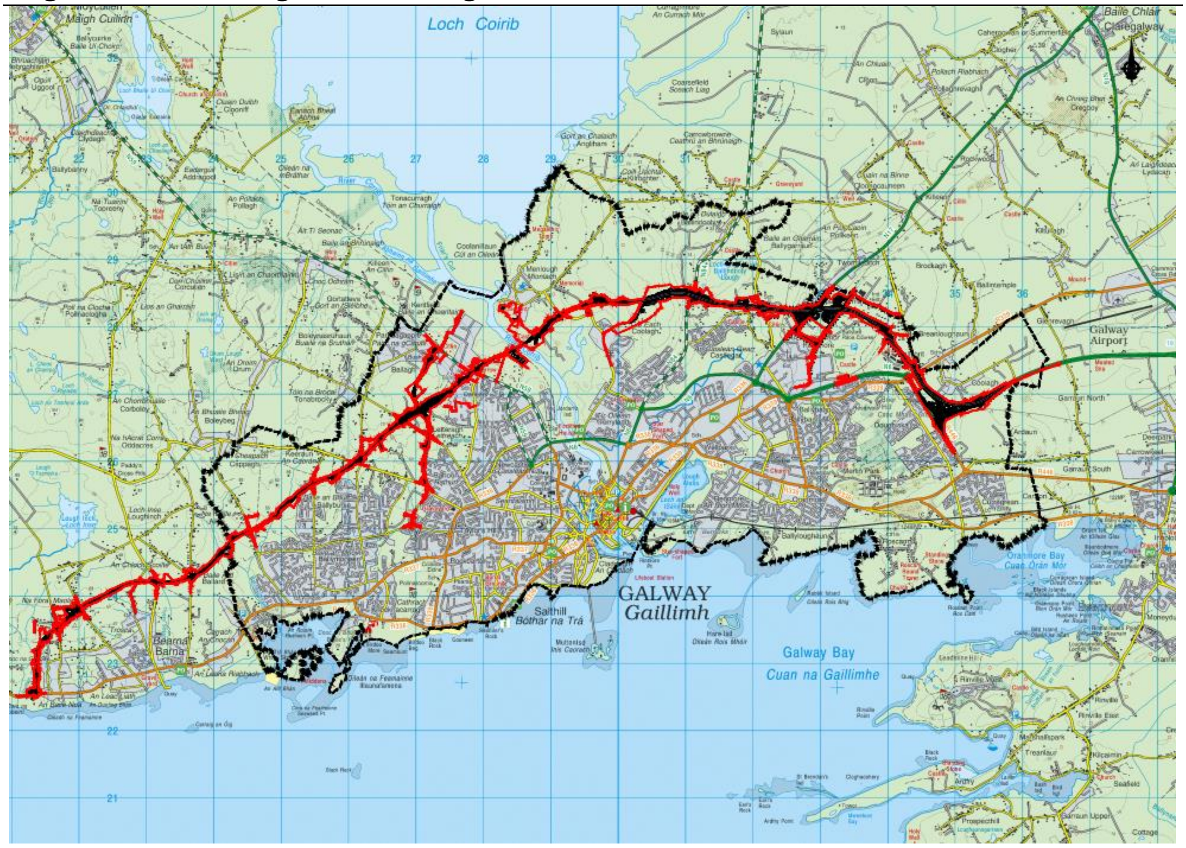


Figure 2.10: N6 Galway City Ring Road Alignment (Galway County Council and Galway City Council, 2020)

Figure 2.11: Existing Crossings over Lough Corrib and River Corrib in Galway (Bing Maps, 2022)

2.4.3.2. Low Emission Zones

The implementation of an LEZ in London in 2008 has been shown to have a considerable impact on the vehicle fleet composition with increased rates of vehicle upgrades from older to newer Euro Classes resulting in lower levels of harmful emissions (Ellison et al., 2013). It was highlighted that the LEZ did not have an impact on flows for some vehicle types such as goods vehicles but had a positive effect on the replacement of older vehicles within all vehicle types. Increased upgrade rates were also noticed in the years prior to the implementation of the zone highlighting the positive impact that planning of these mitigation measures could have on the population and the vehicle fleet compostion. Approximately 51.4% of all UK vehicles were Pre-Euro 3 in 2006 and by the end of 2007 this percentage dropped to 46.2%, prior to the implementation of the London LEZ. London and the surrounding counties had above average statistics for pre-Euro 3 vehicles of approximately 57% at the end of 2007, but by the end of 2011, only 19.4% were pre-Euro 3 compared to the national average of 29.8%.

The introduction of an LEZ or a Congestion Charge and planning around which vehicle types are exempt from the charge can have a substantial impact on vehicle selection when upgrading vehicles. The introduction of a Congestion Charge zone within London and the exemption of hybrid electric vehicles from the charge has seen a substantial uptake in hybrid electric vehicles in the years following its implementation, with hybrid electric vehicle numbers considerably greater in counties / boroughs close to or within the zone (Morton et al., 2017). The study showed that these counties / boroughs had 5 to 55 hybrid electric vehicles per thousand cars whilst counties further from the zone had approximately 0 to 2 hybrid electric vehicles per thousand cars. The introduction of a £12.50 charge in an Ultra LEZ in London reduced average NO_2 concentrations by 29µg/m^3 at the beginning of 2020 (prior to the pandemic). Further reductions in measured concentrations have been observed since then, but these are difficult to assess as restrictions on travel in response to COVID-19 had a major impact on air quality since the beginning of 2020 (Greater London Authority, 2021). LEZs implemented throughout a number of European countries (Denmark, Germany, Netherlands, Portugal, Spain, Italy and the United Kingdom) have achieved significant NO_2 concentration reductions in the range of 4 to 32% (Muller & Le Petit, 2019).

2.4.3.3. Public Service Vehicle Fleet Upgrade

The Irish Bulletin of Vehicle and Driver Statistics report produced annually by the Department of Transport, Tourism and Sport (Department of Transport, Tourism and Sport, 2020) provides details on the Irish vehicle fleet including details relating to fuel type, engine capacities, unladen weight and numerous other breakdowns for each of the vehicle type categories (passenger cars, light commercial vehicles, small public service vehicles, etc.). From 2010 to 2019, the percentage of small public service vehicles fuelled by diesel increased substantially, with increases year on year, from 59% in 2010 to 82% in 2019 (Department of Transport, Tourism and Sport, 2011; Department of Transport, Tourism and Sport, 2012; Department of Transport, Tourism and Sport, 2013; Department of Transport, Tourism and Sport, 2014; Department of Transport, Tourism and Sport, 2015; Department of Transport, Tourism and Sport, 2016; Department of Transport, Tourism and Sport, 2017; Department of Transport, Tourism and Sport, 2018; Department of Transport, Tourism and Sport, 2019). The large public service vehicles fleet also has a high dependency on diesel fuel with approximately 99.91% of all large public service vehicles in every year between 2010 and 2019 being diesel fuelled vehicles. The remaining vehicles were all registered as petrol fuelled except one which was registered as electric in the 2011 register.

The United Kingdom has introduced all-electric powered large public service vehicles in numerous cities and begun plans to have an all-electric powered fleet in a number of cities such as Coventry and Oxford to improve air quality with the aim to reduce air pollution in urban areas by targetting vehicles which are controlled by government authorities (Department for Transport, 2021). In Ireland, there are a number of guidance documents published to specify the particular types of vehicles that are acceptable for use as small public service vehicles in Ireland and to provide limits on the size and age of vehicle (National Transport Authority, 2021). The current limits on the age of small public service vehicles provide a definitive timeline for when this mitigation measure can be fully implemented. The 5 Cities Demand Management Study (Department of Transport, Tourism and Sport & Systra, 2020; Department of Transport, Tourism and Sport & Systra, 2020; Department of Transport, Tourism and Sport & Systra, 2020; Department of Transport, Tourism and Sport & Systra, 2020; Department of Transport, Tourism and Sport & Systra, 2020; Department of Transport, Tourism and Sport & Systra, 2020) highlighted that the city centre areas of 4 of the 5 major cities in Ireland have considerably larger percentages of both small public service vehicles and large public service vehicles in comparison to the national average. Small public service vehicles make up 0.83% of the national average vehicle fleet whilst 8.07%, 2.13%, 1.49%, 2.33% and 0.62% of vehicles within Dublin City, Cork City, Limerick City, Galway City and Waterford City respectively are small public servic vehicles. In the national average vehicle fleet, 0.43% of vehicles are large public service vehicles whilst in Dublin City, Cork City, Limerick City, Galway City and Waterford City the percentages in all cities were greater than the national average at 13.43%, 10.64%, 10.32%, 9.32% and 9.94% respectively. The higher proportion of public service vehicles in urban areas indicates that the transition to greener fuel options within the fleet has the potential to significantly improve air quality in areas which are currently experiencing high levels of air pollution.

2.5. Health Impacts of NO_2

The following section highlights the results of epidemiological studies which have identified potential links between NO_2 exposure and various health effects. Appendix D contains information on international and Irish statistics on health conditions which are commonly linked to NO_2 and other air pollutants as well as information on the symptoms, medication and causes of these health conditions. Further information on confounding factors within epidemiological studies is also provided in Appendix D.

2.5.1. Epidemiological Studies

The United States Environmental Protection Agency has published Integrated Science Assessments (ISA) for a number of air pollutants. These establish the health impacts relating to each individual pollutant by analysing previous international research studies (United States Environmental Protection Agency, 2009; United States Environmental Protection Agency, 2010; United States Environmental Protection Agency, 2008; United States Environmental Protection Agency, 2016). A major issue in determining health impacts is the potential for confounding factors to overestimate or underestimate the results and their determination within the ISAs is based on the potential of those studies to account for and minimise potential confounding. The determination on health impacts is based on categories provided below:

- **Causal** – Studies where exposure concentration statistics are typical for the location of the studies and the results are sufficient to conclude that the pollutant has health impacts independent of confounding factors / copollutants
- **Likely** – Studies where exposure concentration statistics are typical for the location of the studies and the pollutant links to health effects have been confirmed but effects independent from copollutants cannot be fully established
- **Suggestive** – Limited studies available where exposure concentration statistics are typical for the location of the studies but confounding cannot be reduced or sufficient studies are available but results are inconsistent on health impact links.
- **Inadequate** – Insufficient studies available with consistent and statistically strong results available to determine health impacts
- **Not Likely** – Studies covering wide ranges of concentrations typical for the location of the studies have considered vulnerable groups of the population and consistently concluded that there are no health impacts linked to the pollutant at any concentration

In the 2008 Oxides of Nitrogen ISA (United States Environmental Protection Agency, 2008), there was inadequate information available to determine links between most of the investigated health effects and NO_2 exposure, with only short-term and long-term exposure respiratory effects and short-term total mortality having sufficient studies to justify a likely causal or suggestive determination. However, the additional information available for the 2016 ISA (United States Environmental Protection Agency, 2016) had greatly increased and improved knowledge of health impacts across the board, with only the Fertility, Reproduction and Pregnancy and Postnatal Development categories remaining at an Inadequate determination, as shown in Table 2.6. There was sufficient evidence since 2008 to determine that short-term exposure to NO_2 was independently linked to respiratory health effects (United States Environmental Protection Agency, 2016).

Table 2.6: NO_2 Exposure Health Effects (United States Environmental Protection Agency, 2008; United States Environmental Protection Agency, 2016)

Short-Term NO_2 Exposure		
Health Effects	***2008 Determination***	***2016 Determination***
Respiratory	Likely Causal Relationship	Causal Relationship
Cardiovascular	Inadequate to Infer Causal Relationship	Suggestive of Causal Relationship
Total Mortality	Suggestive of Causal Relationship	Suggestive of Causal Relationship

Long-Term NO_2 Exposure		
Health Effects	***2008 Determination***	***2016 Determination***
Respiratory	Suggestive of Causal Relationship	Likely Causal Relationship
Cardiovascular and Diabetes	Inadequate to Infer Causal Relationship	Suggestive of Causal Relationship
Reproductive and Developmental	Inadequate to Infer Causal Relationship	*Fertility, Reproduction and Pregnancy* – Inadequate to Infer Causal Relationship
		Birth Outcomes – Suggestive of Causal Relationship
		Postnatal Development – Inadequate to Infer Causal Relationship
Total Mortality	Inadequate to Infer Causal Relationship	Suggestive of Causal Relationship
Cancer	Inadequate to Infer Causal Relationship	Suggestive of Causal Relationship

The Committee on the Medical Effects of Air Pollutants have published statements with respect to health effects linked with NO_2 exposure and found that there is stronger evidence available confirming these links but that the issue of confounding cannot be fully removed (Committee on the Medical Effects of Air Pollutants, 2015). Results from these studies may still represent multi-pollutant effects using NO_2 as a marker, but there is sufficient evidence to suggest that NO_2 is a partial cause of the effects (Committee on the Medical Effects of Air Pollutants, 2015). A number of meta-analysis studies have been carried out linking NO_2 exposure with increases in respiratory and cardiovascular related hospital admissions and mortality rates (Atkinson et al., 2014; Faustini et al., 2014; Mills et al., 2015).

2.5.1.1. Respiratory NO_2 Health Effects

Asthma exacerbation is the strongest health effect linked to NO_2 short-term exposure, with airway responsiveness observed at 100 ppb (United States Environmental Protection Agency, 2016), which is approximately equal to the hourly limit value set by the World Health Organisation guidelines and EU Directive (World Health Organisation, 2006; European Union, 2008). Short-term international studies have shown increased hospital admissions and ED visits in relation to asthma in the population aged between 5 and 18 years and also increased numbers of respiratory symptoms for people aged 65 years and older, with increasing NO_2 exposure (Andersen et al., 2007). After PM_{10} adjustment, the asthma hospital admissions links to NO_2 were not affected but links to the respiratory disease hospital admissions in the older population were less significant.

Increased NO_2 exposure is also linked to reductions in the various elements of lung function in children such as forced expiratory volume, forced vital capacity and maximal instantaneous forced flow and these results are independent of $PM_{2.5}$ (Moshammer et al., 2006). A single pollutant model analysis of NO_2, $PM_{2.5}$, CO, O_3 and Sulfur Dioxide (SO_2) in relation to forced expiratory volume and peak expiratory flow rate effects in children showed that NO_2 was the pollutant which was most associated with these effects and also had the strongest links to wheeze cough and night time asthma symptoms and missed school days (O'Connor et al., 2008). Further analysis was then carried out on a three pollutant model of NO_2, $PM_{2.5}$, O_3 and effects related to the other pollutants reduced considerably whilst NO_2 effects remained significant.

A study on outdoor air pollution exposure and its effect on asthma in children and adults showed that NO_2 had the strongest links to asthma morbidity in children and the older population during the warmer periods, with less significant links to the population aged between 15 and 64 years old, and this result was robust to adjustment for seasonal viruses, meteorological factors and allergens such as pollen (Villeneuve et al., 2007). Results for other respiratory health effects have been inconsistent, making it more difficult to establish the proportion of health effects which are independent to NO_2 (United States Environmental Protection Agency, 2016). A meta-analysis carried out on studies relating to asthmatics and airway hyper-responsiveness effects found similar levels of effects at varying levels of exposures and this lead to the conclusion NO_2 was not a causal factor (Goodman et al., 2009) but another meta-analysis carried out on these studies analysed links based on both resting and exercising NO_2 exposures and found strong links, in particular, with resting exposures (Brown, 2015).

The Committee on the Medical Effects of Air Pollutants (Committee on the Medical Effects of Air Pollutants, 2016) have found that links between NO_2 exposure and COPD is highly inconsistent with results from a number of studies reporting limited or no links with the pollutant (Euler et al., 1988; Cesaroni et al., 2008; Schikowski et al., 2010). Schikowski et al. (2005) and Sunyer et al. (2006) reported that NO_2 was linked to an increase in chronic phlegm in the female population with the later finding no associations with health effects in the male population. Zemp et al. (1999) found that exposure to NO_2 was associated with chronic cough, chronic phlegm production and breathlessness.

2.5.1.2. Cardiovascular NO_2 Health Effects

A considerable number of studies have been carried out linking NO_2 exposure to various cardiovascular health effects such as ischemic heart disease, cerebrovascular disease and stroke but these fail to account for potential confounding from other pollutants (United States Environmental Protection Agency, 2016). A single pollutant model analysis of cardiovascular disease hospital admissions for people over 65 years old showed minor links with NO_2 exposure but after accounting for PM_{10} this effect was nullified (Andersen et al., 2007). Increasing NO_2 exposure has been shown to have a similar impact on the number of myocardial infarction, angina pectoris and cardiac hospital admissions in a number of European cities and results in relation to cardiac admission from NO_2 in two pollutant models remain stable after adjustment for PM_{10} and O_3 (von Klot et al., 2005). Analyses on myocardial infarction hospital admissions highlighted links with increasing NO_2 exposure and these results were also observed in two-pollutant models with PM_{10}, SO_2, CO and O_3 (Hsieh et al., 2010; Liu et al., 2017). In contrast to Hsieh et al (2010), which found links during both the warm and cold seasons, another study established only links to myocardial infarction hospital admissions in the cold season; results which were also robust to PM_{10}, SO_2, CO and O_3 (Cheng et al., 2009). A number of studies have also found that the impact from NO_2 in relation to myocardial infarction hospital admissions is nullified or considerably reduced after adjustment to CO, SO_2 and black smoke (Poloniecki et al., 1997; Stieb et al., 2009; Nuvolone et al., 2011).

Similar to the ischemic heart disease studies, the resulting effects on cerebrovascular disease and stroke after adjustment for other pollutants can vary considerably from case to case. Cerebrovascular disease hospital admissions have been linked to NO_2 exposure in a two pollutant model with SO_2 (Zheng et al., 2013; Ballester et al., 2001) and in the case of

Zheng et al. (2013), the link is strengthened by adjustment for PM_{10}. In the case of cardiac disease related hospital admissions, Zheng et al. (2013) found that both PM_{10} and SO_2 adjustment strengthened the links to NO_2. Ballester et al. (2001) also found that effects persist after accounting for black smoke. Results from a number of studies have seen temperature having a considerable effect on links between NO_2 and stroke hospital admissions, with Xiang et al. (2013) reporting a link only in cold periods, whilst Villeneuve et al. (2006) and Villeneuve et al. (2012) only established links during warm periods. Villeneuve et al. (2006) found that results for ischemic stroke were robust to SO_2 and CO, were further strengthened by adjustment for $PM_{2.5}$ and PM_{10} and were reduced slightly when accounting for O_3. They also established that results for haemorrhagic stroke were robust to SO_2, O_3, $PM_{2.5}$ and PM_{10} but were nullified when accounting for CO. Villeneuve et al. (2012) found that results for ischemic stroke were robust to SO_2 and were reduced slightly but remained positive when adjusted for CO, O_3 and $PM_{2.5}$. For haemorrhagic stroke, they found that links were reduced, but still positive, by adjustment for SO_2 and $O_{3,}$ and increased by the inclusion of CO and $PM_{2.5}$. Tsai et al. (2003) found that temperature had a considerable effect on results for cerebral stroke and ischemic stroke hospital admissions, with warm temperatures (>20 °C) establishing stronger links with NO_2. In colder temperatures (<20 °C), links to ischemic stroke were weaker, but still positive, and links to cerebral stroke were nullified. Effects related to NO_2 exposure persisted after adjustment for SO_2, CO and O_3 in two pollutant models, whilst PM_{10} slightly reduced links between NO_2 and cerebral and ischemic stroke.

The Committee on the Medical Effects of Air Pollutants (Committee on the Medical Effects of Air Pollutants, 2018) reported that results linking NO_2 exposure to effects on cardiac function are inconsistent, with results from studies varying considerably. While some studies have observed high correlations between NO_2 exposure and independent effects on heart rate variability, other studies identified no links between the pollutant and the health effects (Zanobetti et al., 2010; Mills et al., 2011; Huang et al., 2012; Scaife et al., 2012).

2.6. NO_2 Modeling Approaches

The following section describes various modelling approaches that are commonly used to predict NO_2 concentrations. The theory, assumptions, limitations and accuracy of each of the approaches are introduced.

2.6.1. Dispersion Modelling

Dispersion modelling is a process which approximates pollution concentrations and the dispersion pattern of a pollutant based on information on the pollution source and the surrounding environment (Environmental Protection Agency, 2019). Source information include the stack height, stack diameter, exit velocity, exit temperature, emission rate and volume flow. Information on the surrounding environment includes meteorological conditions, land use, building layout, terrain and the location of the receptor relative to the source. A number of approaches have been used for Air Dispersion Modelling and these include:

- Box Model
- Gaussian Model
- Lagrangian Model

The Box Model approach assumes the air supply of a region is contained within a box (Reed, 2005). Limitations of this approach include that the pollutant concentration within the box is assumed homogenous and the average concentration estimates are based on a significantly large area (Reed, 2005). Equation 2.3 shows the calculation of pollutant concentrations using the Box Model approach.

$$\frac{dCV}{dt} = QA + uC_{in}WH - uCWH$$

Eqn. 2.3: Box Model Equation (Reed, 2005)

Where:

Q = Pollutant Emission Rate

C = Homogenous Concentration within Box

V = Volume of Box

C_{in} = Pollutant Concentration Entering Box

A = Top / Bottom Area of Box (Length x Width)

u = Wind Speed Normal to Box

H = Mixing Height

The Gaussian Model is the most common approach and it assumes the dispersion of a pollutant follows a similar pattern to a normal statistical distribution, as shown in Equation 2.4 and Figure 2.12. This approach also assumes the emission and wind conditions are constant and the diffusion of the pollutant in the downwind direction is negligible relative to the lateral and vertical diffusion (Reed, 2005).

$$X = \frac{Q}{2\pi u_s \sigma_y \sigma_z}\left[exp\left\{-0.5\left(\frac{y}{\sigma_y}\right)^2\right\}\right]\left[exp\left\{-0.5\left(\frac{H}{\sigma_z}\right)^2\right\}\right]$$

Eqn. 2.4: Gaussian Model Equation (Reed, 2005)

Where:

X = Hourly Concentration at Receptor (Distance x from Source)

Q = Pollutant Emission Rate

u_s = Mean Wind Speed at Exit Height

σ_y σ_z = Standard Deviation of Lateral and Vertical Concentration Distribution

y = Crosswind Distance from Plume Centreline

H = Emission Source Height

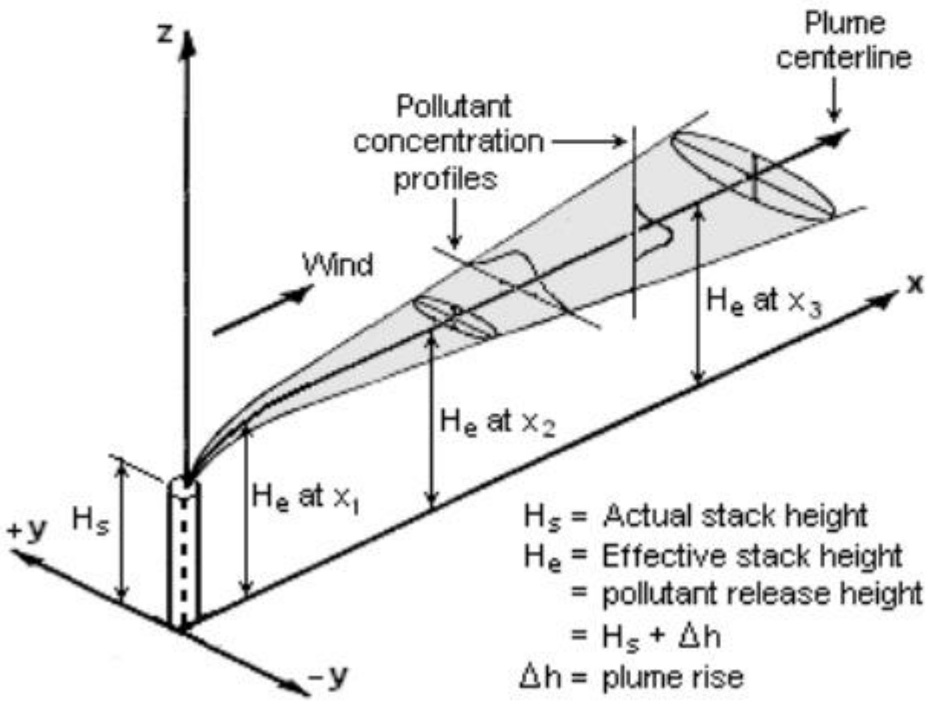


Figure 2.12: Gaussian Dispersion Model Method for Pollutant Estimation (Vannucci et al., 2008)

The Lagrangian Model approach estimates dispersion of a pollutant based on a moving grid and the movement of the grid is usually based on the predominant wind direction (Reed, 2005). This approach is limited when comparing results of the model with actual measurements, as actual measurements are taken at stationary points whilst this modelling approach estimates concentrations based on a moving grid. The inclusion of a Eulerian reference grid can compensate for this weakness in validating the model (Reed, 2005). Equation 2.5 identifies the process of calculating pollutant concentration using the Langrangian Model approach.

$$\langle c(r,t)\rangle = \int_{-\infty}^{t} \int p(r,t|r',t')\, S(r',t')\, dr'dt'$$

Eqn. 2.5: Lagrangian Model Equation (Reed, 2005)

Where:

<c(r,t)> = Average Concentration at Location, r at Time, t

S(r',t') = Pollutant Emission at Source

p(r,t|r',t') = Probability Function that Air is Moving from Location r' (Location at Source) to r from Time t' (Time at Source) to t

A range of Air Dispersion Modelling software is available such as AERMOD, ADMS 5 and CALPUFF and the software should be selected based on the results required as limitations of modelling software can vary significantly (Environmental Protection Agency, 2019). Scenarios such as calm meteorological conditions, turbulent dispersion patterns experienced in coastal regions (known as coastal fumigation) and terrain downwash can lead to increased ambient concentrations of pollutants and the capability of the software mentioned above to model these scenarios may be limited. Advanced dispersion models have fewer limitations but to achieve accurate results, they require significant amounts of data and data processing prior to utilising models, have complex relationships between variables and result in increased time and computation costs (Briggs, 2007; Šimić et al., 2020; Xiang et al., 2020; Environmental Protection Agency, 2019). A number of studies utilising various Air Dispersion Modelling software achieved cross validation R^2 between 0.04 and 0.83 for NO_2 (Briggs, 2005; Benson, 1992; Karppinen et al., 2000; Kukkonen et al., 2001).

2.6.2. Land Use Regression (LUR) Modelling

Land Use Regression (LUR) Modelling aims to produce a regression equation which can estimate pollutant concentrations at any location based on the surrounding land use (European Union, 2010; Donnelly et al., 2019; Aeroqual, 2021). Values for potential predictor variables (potential sources of pollution) at measured pollutant locations are captured using Geographic Information Systems (GIS). Statistical associations between potential predictor variables and measured pollutant concentrations are determined using regression techniques. This determines the predictor variables which are linked to pollutant levels at a study location and produces regression coefficients which are applied to the predictor variables within the LUR equation.

The European Study of Cohorts for Air Pollution Effects (ESCAPE) project identified a standardised approach for the development of LUR models and analyzed the accuracy of the models across 36 regions (Beelen et al., 2013). A large range of predictor variables were identified within the study which were assessed within the model for each of the 36 regions, as shown in Table 2.7. Variables were only included in the final model if (European Union, 2010; Beelen et al., 2013):

i. The adjusted R^2 increased by more than 1%
ii. The direction of effect of the variable does not change
iii. The variable does not change the direction of effect of previously included variables in the model

Table 2.7: ESCAPE Project LUR Model Predictor Variables (European Union, 2010)

Category	Units	Buffer Radius (m)	Transformation
Background Variables			
Coordinate Variables	m	N/A	N/A
High Density Residential Land	m^2	100, 300, 500, 1 000, 5 000	N/A
Low Density Residential Land	m^2	100, 300, 500, 1 000, 5 000	N/A
Industry	m^2	100, 300, 500, 1 000, 5 000	N/A
Port	m^2	100, 300, 500, 1 000, 5 000	N/A
Urban Green	m^2	100, 300, 500, 1 000, 5 000	N/A
Semi-Natural and Forested Areas	m^2	100, 300, 500, 1 000, 5 000	N/A
Local Land Use	m^2	100, 300, 500, 1 000, 5 000	N/A
Population	Number	100, 300, 500, 1 000, 5 000	N/A
Households	Number	100, 300, 500, 1 000, 5 000	N/A
Altitude	m	N/A	Square Root
Traffic Variables			
Traffic on Nearest Road	Vehicle Day^{-1}	N/A	N/A
Distance to Nearest Road	m^{-1} / m^{-2}	N/A	Inverse Distance / Inverse Distance Squared
Product of Flow and Inverse Distance to Nearest Road	Vehicle m^{-1} Day^{-1} Vehicle m^{-2} Day^{-1}	N/A	N/A

Category	Units	Buffer Radius (m)	Transformation
Traffic on Nearest Major Road	Vehicle Day^{-1}	N/A	N/A
Distance to Nearest Major Road	m^{-1} / m^{-2}	N/A	Inverse Distance / Inverse Distance Squared
Product of Flow and Inverse Distance to Nearest Major Road	Vehicle m^{-1} Day^{-1} Vehicle m^{-2} Day^{-1}	N/A	N/A
Total Traffic Load (Product of Flow and Length) of All Major Roads in Buffer	Vehicle m Day^{-1}	25, 50, 100, 300, 500, 1 000	N/A
Total Traffic Load (Product of Flow and Length) of All Roads in Buffer	Vehicle m Day^{-1}	25, 50, 100, 300, 500, 1 000	N/A
Heavy-Duty Traffic Flow on Nearest Road	Vehicle Day^{-1}	N/A	N/A
Total Heavy-Duty Traffic Load (Product of Flow and Length) of All Major Roads in Buffer	Vehicle m Day^{-1}	25, 50, 100, 300, 500, 1 000	N/A
Total Heavy-Duty Traffic Load (Product of Flow and Length) of All Roads in Buffer	Vehicle m Day^{-1}	25, 50, 100, 300, 500, 1 000	N/A
Road Length of All Roads in Buffer	m	25, 50, 100, 300, 500, 1 000	N/A
Road Length of All Major Roads in Buffer	m	25, 50, 100, 300, 500, 1 000	N/A
Distance to Nearest Road	m^{-1} / m^{-2}	N/A	Inverse Distance / Inverse Distance Squared
Distance to Nearest Major Road	m^{-1} / m^{-2}	N/A	Inverse Distance / Inverse Distance Squared
Aspect Ratio (Sum Height of Buildings Both Sides of Road Divided by Road Width)	m / m	N/A	N/A

The ESCAPE project identified significant spatial variations across all regions within the analysis (Beelen et al., 2013). Therefore, the LUR model equation developed for each of the regions had significant differences in the regression coefficients and predictor variables included in the final model. All LUR equations for the 36 regions included a traffic variable but the buffer sizes, route types and traffic types for each of the predictor variables were different for the majority of the regions.

The cross-validation R^2 of LUR models identified by Briggs (2007) were between 0.45 and 0.7 and had standard errors less than 20%, which is similar to results that would be expected from advanced dispersion models (Briggs, 2007; Briggs et al., 1997; Briggs et al., 2000; Gilbert et al., 2005; Briggs, 2005). Development of LUR models for 36 different regions in Europe as part of the ESCAPE project also generated strong results, with cross validation R^2 between 0.55 and 0.92 (Beelen et al., 2013).

Recent studies which utilised LUR models to estimate various air pollutants in areas throughout the world also achieved significant results using different combinations of predictor variables. Jones et al. (2020) captured 66% of the spatial variability in Ultrafine Particles (UFPs) in Southern California using a combination of the following variables:

- Inverse distance from LAX airport
- NO_2 background concentrations from a spatiotemporal model
- Percentage of area within a 1km buffer that is categorised as airport
- Major highways total length within 50m of study location
- Percentage of area within 5km buffer that is classified as highly developed
- Passenger vehicle traffic intensity within 1km
- Percentage of area within 5km buffer that is categorised as deciduous forest
- Percentage of area within 1km buffer that is categorised as cultivated crops
- Percentage of area within 5km buffer that is categorised as mixed forest
- Percentage of area within 50m buffer that is classified as medium intensity developed
- Percentage of area within 100m buffer that is classified as open space developed
- Percentage of area within 50m buffer that is classified as highly developed

A study in the Netherlands by Lu et al. (2020) found that LUR captured 61% of the spatial variability of NO_2 within the city of Utrecht. Predictor variables which were included in the final model of this study were predominantly traffic based due to the links between NO_2 pollution and the transport industry and these include:

- Total road length within 1km buffer of study location
- Total road length within 5km buffer of study location
- Total major road length within 25m buffer of study location
- Heavy traffic load within 50m buffer of study location

Liu et al. (2019) produced an annual NO_2 concentration LUR model for Xi'an in China and achieved an adjusted R^2 of greater than 0.85. The predictor variables for this study included total land use area categorised as green area within the 500m buffer, total land use area categorised as residential within the 1km buffer, the distance to the three nearest polluting factories and total area categorised as road within 3km buffer. A fine particulate matter concentration LUR model developed by Ross et al. (2007) for the New York City region captured approximately 64% of the spatial variability of the pollutant. The predictor variables within the model were the number of 1000s of vehicle kilometers per hour within the 500m buffer, the population in terms of 1000s within the 1km buffer and total area categorised as industrial land use within the 300m buffer in terms of acres.

A study by Eeftens et al. (2016) developed LUR models for 10 regions in Switzerland which achieved adjusted R^2 values in the range of 0.46 and 0.89. The environments in each of the regions varied considerably therefore, the combination of predictor variables and buffer sizes for the variables were also unique to each of the regions. The predictor variables included in this analysis included:

- Total area covered by buildings
- Size of the population
- Land use categories (low and high density residential, airport, industrial, natural, port, urban green / natural land and water)
- Total length of roads / major roads
- Total traffic / heavy traffic distance travelled on major / all roads
- Inverse distance to nearest major roads
- Altitude

A study of NO_2 estimation using an LUR approach completed by Shi et al. (2020) along a transportation corridor in Mississauga, Canada captured 69% of spatial variability in NO_2. The final model predictor variables included the daily traffic flow within the 200m buffer, the total length of major roads within the 50m buffer, the total area of land categorised as government and institutional land use within the 500m buffer, the distance to the nearest major intersection, the total length of minor roads within the 100m buffer and the total area of land categorised as parks and recreational land use within the 500m buffer.

An NO_2 LUR model developed by Naughton et al. (2018) for the Republic of Ireland introduced an additional level of detail which applied weightings based on the wind direction proportions at a study location, known as a Wind Sector Land Use Regression (WS-LUR) model. Therefore, sources of NO_2 / predictor variables located within the predominant wind direction sectors had heavier weightings than predictor variables in other wind direction sectors. This approach produced results which were similar to the strongest models described above, with 78% of the spatial variability in NO_2 captured by the model.

2.7. Conclusion

The extent of the previous research studies carried out on NO_2 related health effects has improved knowledge of the health conditions which are most associated with exposures to the pollutant, with asthma incidence and exacerbation having the strongest link. Knowledge in relation to other respiratory diseases and cardiovascular diseases is still uncertain due to inconsistent results, but are still useful, as NO_2 can be used as a marker for the health effects from multi-pollutant exposure. The development of vehicle emission standards to date has substantially improved emissions from all vehicle types but the transport sector is still the largest source of NO_2, which highlights the need for strategies to be introduced targeting the types of vehicles being purchased and the use of those vehicles.

As identified by the literature above the LUR modelling approach has been utilised effectively across a wide range of environments and can achieve accuracies similar to the dispersion modelling approach which requires data with greater levels of detail and increased computing time and costs. The literature highlighted that the LUR modelling variables / equations can vary significantly based on the environment being modelled and that the LUR model approach was applied effectively to Ireland. The Irish model utilised an extended LUR approach known as WS-LUR which applied a weighting based on wind directional sectors and captured a significant proportion of the spatial variability of NO_2.

The review of existing LUR models identified significant variations in traffic based variables, with some LUR models utilising an Annual Average Daily Traffic (AADT) based variable which is a vehicle flow consisting of multiple vehicle types and other LUR models with traffic variables which only account for one vehicle type flow. Therefore, these LUR models do not have the capability of identifying the effects of each of the vehicle types on pollution in a specific location and they also do not account for other vehicle factors which can impact pollution rates such as vehicle age and fuel types. The Irish WS-LUR model provides a solid foundation for the proposed extension to the LUR modelling approach which aims to account for the vehicle fleet breakdown which can vary significantly across routes and therefore improve model accuracy. The development of an LUR model in a format which can be easily accessed and utilised by professionals will assist in backcasting and forecasting pollutant concentrations and also has the potential to be used to estimate concentration changes due to mitigation measures and vehicle fleet changes.

3. Model Development

In this chapter, the background to the NO_2 model employed in this project is introduced and the theory for the model improvements, in the form of more detailed traffic inputs, is also described. The main sources of all the data utilised to develop the model and the methodology for processing the data are introduced. The model development supports the objectives of this element of the research, which were to determine the main environmental, meteorological and traffic related conditions which contribute to high NO_2 levels at various locations.

This required the collection of a considerable amount of data which is represented as a land use regression-based model that can be used to determine the NO_2 concentration at any location in Ireland. Model data was compiled for three pre-set years, 2016 to 2018, allowing the modeller to determine the average annual NO_2 concentration at any location in any of these years. The model also includes a manual entry option that allows the modeller to calculate the average NO_2 concentration at any location for a time period outside of the pre-set years.

The procedure adopted was that developed by Naughton et al. (2018) in the form of a wind sector land use regression (WS-LUR) model to determine the annual mean NO_2 exposure levels at any point in Ireland. The core of the methodology developed by Naughton et al. (2018), as described in Section 3.1 below, was retained but the capability of the model to capture the effects of vehicle emissions was enhanced. This involved including additional data describing the national distribution of vehicle characteristics, including vehicle fleet breakdown, Euro classifications and fuel types. These data were introduced to further strengthen the correlation of the model with local measured concentrations and to enable the analysis of mitigation strategies that reduce emissions in specific locations, or from specific classes of vehicle.

The alterations to the model account for the vehicle fleet breakdown when modelling traffic variables and hence provide a better representation of the type of routes (high levels of Heavy Duty Vehicles (HDVs), mainly cars, public transport routes) surrounding a study location and the resulting NO_2 concentration. These alterations support subsequent research presented in Chapter 6, in which mitigation measures are identified and evaluated by ensuring that the model will be able to analyse the resulting changes in NO_2 concentration by altering the vehicle fleet breakdown and other relevant variables.

3.1. Original Modelling Methodology

The original methodology used in the Naughton et al. (2018) calculated NO_2 concentrations using a wind sector-land use regression (WS-LUR) model approach. Wind sector-based regression was found to be the best option for modelling air pollution concentrations in areas with a complex spatial distribution of sources and where the prevailing wind varies considerably. The calibration of the method was based on analysis of mean concentrations at each of the EPA ambient air quality monitoring sites. This involved (i) dividing the measured hourly concentrations into 8 parts representing measurements obtained during winds from different wind direction sectors and (ii) factoring the measured concentration values to reduce seasonal and diurnal bias in each sector arising due to the tendency of concentrations to be higher during winter months and at certain times of day. The eight sectors at each monitoring station were then further divided into 8 buffer zones with minimum and maximum sector radii varying between 25m and 5km, as shown in Figure 3.1.

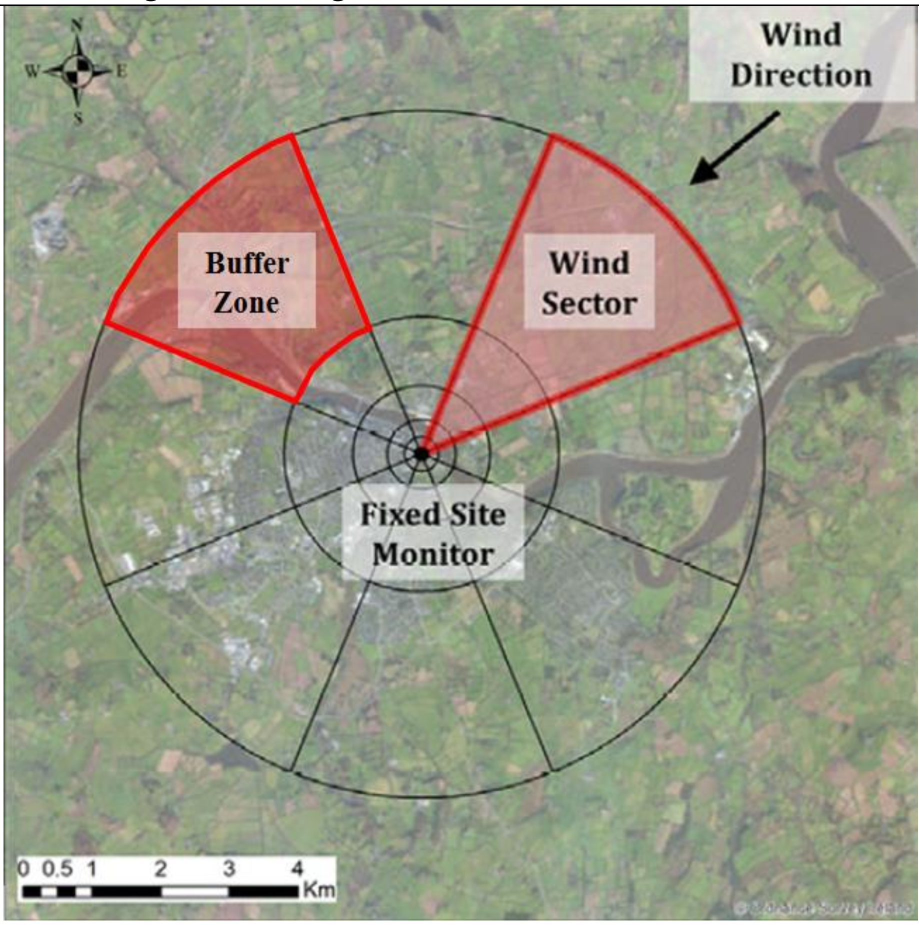


Figure 3.1: WS-LUR Wind Sectors and Buffers (Naughton et al., 2018)

Data was gathered for a large number of candidate predictor variables describing local spatial distributions of pollutant sources, with a focus on variables relating to the traffic and background characteristics of the location, as presented in Table 3.1. These candidate predictor variables were analysed initially to determine if they were correlated with measured NO_2 concentrations. In terms of traffic, the analysed source parameters included road length, road proximity and traffic flow, while the background variables included land cover type, population density, property density, residential heating, household car ownership and proximity to coast. The other variables included large point source pollutant emissions, elevation and wind speed. A weighting parameter was employed to calculate a weighted traffic flow for each of the buffer radii. Each predictor variable was designated a direction of effect and a univariate regression analysis was completed on all variables.

Table 3.1: WS-LUR Initial Model Variables (Naughton et al., 2018)

Category	Units	Sector Radius (m)	Subcategory
Traffic Variables			
Road Length	km	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	All Roads National Road Regional Road Local Road Major Road
Proximity to Road	km^{-1}, km^{-2}	N/A	Nearest Road Nearest Major Road
Traffic Flow	Vehicle km	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	N/A
Weighted Traffic Flow	Vehicle km	N/A	Inverse Distance Gaussian
Background Variables			
Land Cover	Hectares	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	High Density Residential Low Density Residential Industry Port Urban Green Agricultural Semi-Natural and Forested Natural Sea / Ocean
Population Density	Persons / km^2	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	N/A
Property Density	No. properties	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	Residential Commercial
Residential Heating	Properties per heating type	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	Solid Gas Electricity Oil
Household Cars	Cars	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	N/A
Proximity to Coast	km	N/A	N/A
Point Source (PRTR)	kg	25, 50, 100, 250, 500, 1 000, 2 000, 5 000	N/A
Elevation	m	N/A	N/A
Wind Speed	m / s	N/A	N/A

The initial model was created using the variable with the highest R^2 value. Then additional predictor variables were consecutively included, but were only retained if the overall R^2 value increased by at least 1%, the direction of effect of the new variable is as a priori defined, and the new variable does not result in a change in the direction of effect of the previously included variables (Naughton et al., 2018). The variance inflation factor was used to determine which variables should be omitted because little or no correlation was found. The variables which produced the highest adjusted R^2 value were included in the final model, excluding any variable which had a p-value greater than 0.05. The variables which produced the best results for concentration predictions in the analysis completed by Naughton et al. (2018) were inverse distance weighted vehicle kilometres in all buffers from 25m to 5km radii, the number of commercial buildings within a 1km radius, the fraction of land which is categorised as agricultural land within a 1km radius, road density within a 250m radius and the average wind speed. Sources of data for these variables, the effective sector radii and regression coefficients for the final model are shown in Table 3.2. The data required were obtained from Ordnance Survey Ireland (OSI), Transport Infrastructure Ireland (TII), the National Transport Authority (NTA) and Met Éireann and data processing and analysis was performed in Microsoft Excel and ArcGIS.

Due to the relatively small number of fixed monitoring stations for which data was available, model validation adopted a leave-one-out approach to compare the predicted and measured concentrations (Naughton et al., 2018). A 50m x 50m grid was created and at each grid point the model concentration was calculated as the sum of eight weighted sector values (Equation 3.1). The model predictor variable quantities, P_j, were computed separately for each sector, and the resulting modelled sectoral concentrations were weighted based on the frequency of the wind direction during the monitoring period, Wf_i. Equation 3.1 identifies how these weighting factors and regression coefficients for each variable are applied to determine the concentration at a location. Variables such as road length and traffic flow which were initially rasterized using 5m x 5m grid cells were increased to 25m x 25m grid cells to reduce processing time without loss of accuracy.

$$C = \alpha_0 + \sum_{i=1}^{8} \sum_{j=1}^{M} Wf_i \, \alpha_j P_j$$ **Eqn. 3.1: Modelled WS-LUR Concentration Formula (Naughton et al., 2018)**

Where:

C = Ambient wind-dependent background pollutant concentration

i = Wind sectors

j = Terms of the regression equation

Wf_i = Fraction of hourly wind directions within sector i

α_j = Regression coefficient j

α_0 = Constant

P_j = Predictor variable j (Naughton et al., 2018)

The following sections describe the collation of the land use and meteorological data required to define the values of the predictor variables and wind direction fractions used in Equation 3.1.

Table 3.2: WS-LUR Final Model Variables (Naughton et al., 2018)

Predictor	Source	Sector Radius	Coefficient	SE Coefficient
Constant			8.9535	0.74
Inverse Distance Weighted Vehicle km Travelled (IDWVKT)	NTA	0.025 – 5 km (25m, 50m, 100m, 250m, 500m, 1km, 2km, 5km)	2.88E-05	2.5E-06
Commercial Buildings	Geodirectory/An Post	1 km	0.002753	0.000833
Natural / Agricultural Land Use	EEA/CORINE	1 km	-9.1E-06	1.28E-06
Average Wind Speed	Met Éireann		-0.8304	0.1511
Road Density	NTA	0.25 km	0.002664	0.000886

3.2. Detailed Traffic Emissions Modelling

The original model considered only the Annual Average Daily Traffic (AADT) flows within the Inverse Distance Weighted Vehicles Kilometres Travelled (IDWVKT) variable. The AADT is the average daily total flow in both directions passing through a point on a route, based on a full calendar year (Transport Infrastructure Ireland 2016). The AADT flow consists of a number of vehicle types which have considerably different properties such as engine sizes and vehicle weights, with varying levels of emissions. Locations with atypical vehicle type distributions will therefore be less accurately represented within the WS-LUR model. Moreover, since 1993, vehicle emission standards have led to considerable changes in vehicles to reduce emissions, whilst transport policies have had major impacts on the fuel type breakdown of the Irish vehicle fleet (European Union 2012; European Union 2007; European Union 1998; European Union 1994; European Union 1991; Department of Transport, Tourism and Sport 2019). It was important to incorporate such significant changes to the vehicle fleet composition to offset a potential significant weakness when utilising the original regression coefficients (shown in Table 3.2), in an analysis of future or past time periods outside of the original study period, between 2010 and 2012.

To address this issue, the method used to define traffic emission effects in the WS-LUR concentration formula was improved, leading to the altered version of the formula presented in Equation 3.2. The improvement focuses on splitting the AADT element of the IDWVKT predictor variable into separate components for each vehicle type. This is done by defining a unit reference vehicle to which NO_2 emissions from all vehicle types and Euro classifications could be compared. Since the regression coefficients were based on the original AADT-based IDWVKT variable, in which all vehicles are considered equal, the reference unit vehicle is a vehicle with the average emission rate from the period being studied. This ensures that when analysing a time period using the original or new WS-LUR concentration model formula, shown in Equation 3.2, the same result will be achieved when the vehicle distribution is equal to the national average. The emission weighting of each vehicle type / Euro class is defined relative to this standard unit vehicle. The formula for determining the NO_2 emission weighting is shown in Equation 3.3 and a detailed breakdown of its calculation is described in Section 3.3.5.

$$C = \alpha_0 + \sum_{i=1}^{8} \sum_{j=1}^{M} W f_i \, \alpha_j P_j$$ **Eqn. 3.2: WS-LUR Concentration Formula and IDWVKT Variable**

in which:

Original Model IDWVKT: $P_j = {}^{1}/_{\mathrm{d}}$ (AADT x Road Length)

d = Distance to receptor location

$AADT = \sum_{\mathrm{k}=1}^{\mathrm{n}} \mathrm{N_k}$

New Model IDWVKT: $P_j = {}^{1}/_{\mathrm{d}}$ (EAADT x Road Length)

d = Distance to receptor location

$EAADT = \sum_{\mathrm{k}=1}^{\mathrm{n}} \mathrm{E_k N_k}$

E_k = Emission weighting for vehicle category k

N_k = No. of vehicles in category k (Euro class or vehicle type)

$$E_k = {}^{e_v}/_{e_A}$$ **Eqn. 3.3: NO2 Emission Weighting Calculation**

Where:

e_V = Average emission from vehicle type v in a study period

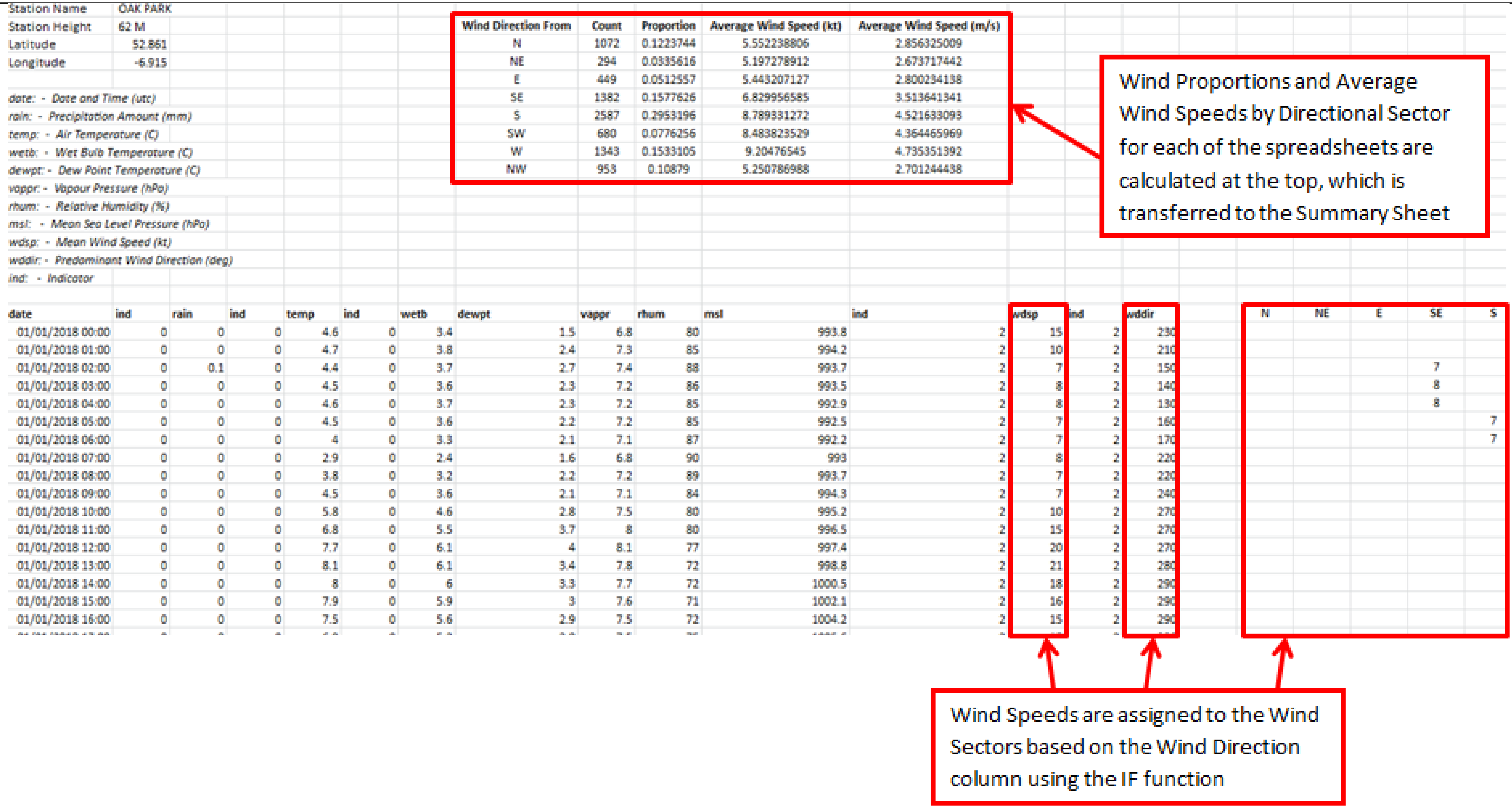
e_A = Average emission from all vehicles in a study period

The European Monitoring and Evaluation Programme (EMEP) / European Environment Agency (EEA) Air Pollutant Emission Inventory Guidebook (European Environment Agency, 2019) identifies the average NO_X emission in grams / km for each vehicle type and Euro class, including pre-Euro vehicles classes, as well as an NO_2 fraction (f-NO_2), for each fuel type, which determines the amount of NO_2 emitted based on the quantity of NO_X emitted. This document is used by the Member States of the European Union to assist the process of emission reporting as part of the National Emission Ceilings Directive and to ensure consistent reporting by each country in their aim to achieve emission targets. This information was used to determine the typical NO_2 emission rate for each type of vehicle, which was then divided by the all-vehicle average emission rate during the time period being studied to determine the NO_2 emission weighting for the vehicle type. The Irish Bulletin of Vehicle and Driver Statistics (Department of Transport, Tourism and Sport, 2019; Department of Transport, Tourism and Sport, 2018; Department of Transport, Tourism and Sport, 2017; Department of Transport, Tourism and Sport, 2016; Department of Transport, Tourism and Sport, 2015; Department of Transport, Tourism and Sport, 2014; Department of Transport, Tourism and Sport, 2013; Department of Transport, Tourism and Sport, 2012; Department of Transport, Tourism and Sport, 2011) has been published on a yearly basis since 2010 and collates data relating to the entire Irish vehicle fleet, such as first year of registration, unladen weight, engine capacity and fuel type, which was utilised to determine the Euro Classification breakdown of the vehicle fleet.

3.3. Model Data

3.3.1. Meteorological Data

Meteorological data were retrieved from the Met Éireann website (Met Éireann, 2019). All monitoring stations, including offshore stations, were included in the analysis to achieve the most accurate representation of conditions throughout the country and in particular around coastal areas. Data analysis was carried out on each station to determine the average temperature, average precipitation, average relative humidity, average wind speed and proportions by wind sector, as shown in Figure 3.2.



Station Name	OAK PARK
Station Height	62 M
Latitude	52.861
Longitude	-6.915
date: - Date and Time (utc)	
rain: - Precipitation Amount (mm)	
temp: - Air Temperature (C)	
wetb: - Wet Bulb Temperature (C)	
dewpt: - Dew Point Temperature (C)	
vappr: - Vapour Pressure (hPa)	
rhum: - Relative Humidity (%)	
msl: - Mean Sea Level Pressure (hPa)	
wdsp: - Mean Wind Speed (kt)	
wddir: - Predominant Wind Direction (deg)	
ind: - Indicator	

Wind Direction From	Count	Proportion	Average Wind Speed (kt)	Average Wind Speed (m/s)
N	1072	0.1223744	5.552238806	2.856325009
NE	294	0.0335616	5.197278912	2.673717442
E	449	0.0512557	5.443207127	2.800234138
SE	1382	0.1577626	6.829956585	3.513641341
S	2587	0.2953196	8.789331272	4.521633093
SW	680	0.0776256	8.483823529	4.364465969
W	1343	0.1533105	9.20476545	4.735351392
NW	953	0.10879	5.250786988	2.701244438

date	ind	rain	ind	temp	ind	wetb	dewpt	vappr	rhum	msl	ind	wdsp	ind	wddir	N	NE	E	SE	S
01/01/2018 00:00	0	0	0	4.6	0	3.4	1.5	6.8	80	993.8	2	15	2	230					
01/01/2018 01:00	0	0	0	4.7	0	3.8	2.4	7.3	85	994.2	2	10	2	210					
01/01/2018 02:00	0	0.1	0	4.4	0	3.7	2.7	7.4	88	993.7	2	7	2	150				7	
01/01/2018 03:00	0	0	0	4.5	0	3.6	2.3	7.2	86	993.5	2	8	2	140				8	
01/01/2018 04:00	0	0	0	4.6	0	3.7	2.3	7.2	85	992.9	2	8	2	130				8	
01/01/2018 05:00	0	0	0	4.5	0	3.6	2.2	7.2	85	992.5	2	7	2	160					7
01/01/2018 06:00	0	0	0	4	0	3.3	2.1	7.1	87	992.2	2	7	2	170					7
01/01/2018 07:00	0	0	0	2.9	0	2.4	1.6	6.8	90	993	2	8	2	220					
01/01/2018 08:00	0	0	0	3.8	0	3.2	2.2	7.2	89	993.7	2	7	2	220					
01/01/2018 09:00	0	0	0	4.5	0	3.6	2.1	7.1	84	994.3	2	7	2	240					
01/01/2018 10:00	0	0	0	5.8	0	4.6	2.8	7.5	80	995.2	2	10	2	270					
01/01/2018 11:00	0	0	0	6.8	0	5.5	3.7	8	80	996.5	2	15	2	270					
01/01/2018 12:00	0	0	0	7.7	0	6.1	4	8.1	77	997.4	2	20	2	270					
01/01/2018 13:00	0	0	0	8.1	0	6.1	3.4	7.8	72	998.8	2	21	2	280					
01/01/2018 14:00	0	0	0	8	0	6	3.3	7.7	72	1000.5	2	18	2	290					
01/01/2018 15:00	0	0	0	7.9	0	5.9	3	7.6	71	1002.1	2	16	2	290					
01/01/2018 16:00	0	0	0	7.5	0	5.6	2.9	7.5	72	1004.2	2	15	2	290					

Figure 3.2: Meteorological Data Analysis Example (Data Source: Met Éireann, 2019)

A summary sheet was prepared to reduce the volume of data that needs to be included in key formulas within the model, which assists with model performance. Results for individual parameters, for each pre-set year, at every monitoring station are provided in the summary sheet, as shown in Figure 3.3.

When calculating the ambient NO_2 concentration at a given location, the distances to each of the meteorological monitoring stations are calculated in the summary sheet, based on the co-ordinates of the study location entered by the modeller, as described in Section 4.1.1. The closest stations to the study location are determined, and the meteorological conditions at the study location are determined by interpolation. The modeller has an option to declare the number of influencing stations by altering the Triangulation Accuracy (No. of Dependent Points) in the Input Sheet, as described in Section 4.1.1.

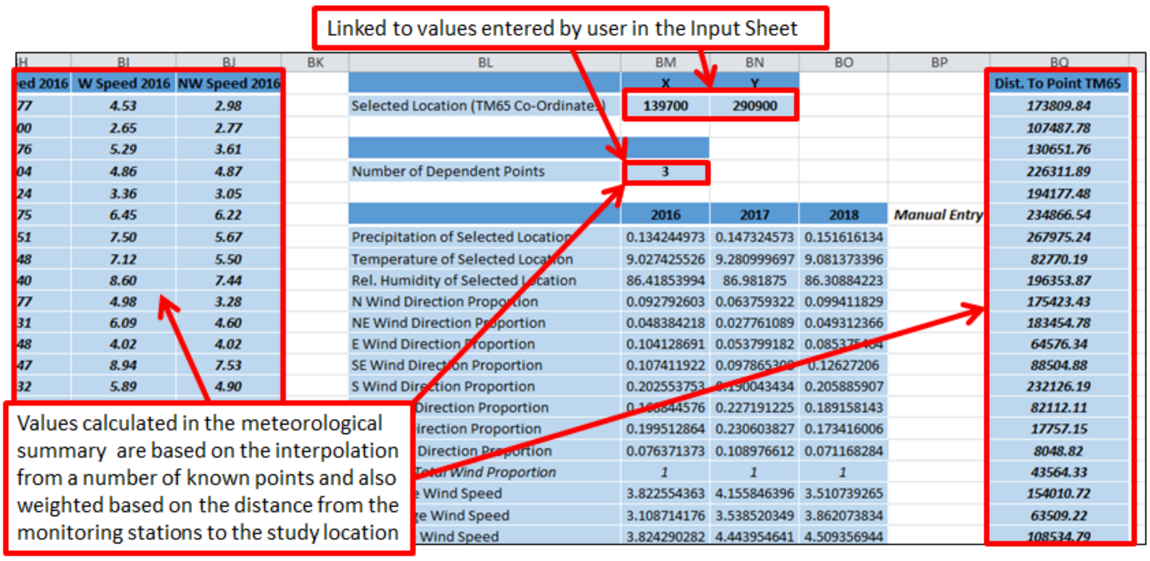


Figure 3.3: Meteorological Data Summary Sheet

A combination of IF, SMALL, INDEX, MATCH and CHOOSE functions is used to calculate the values of meteorological variables at a specific location using an inverse distance weighted approach as shown in Equation 3.4. The values for each meteorological variable (8 wind direction speeds, 8 wind direction proportions, temperature, precipitation and relative humidity) calculated using this formula are then transferred to the model to calculate the NO_2 concentration at the location specified by the modeller.

$$f_0 = \left(1/_{d_1}\right) f_1 + \left(1/_{d_2}\right) f_2 + \cdots + \left(1/_{d_n}\right) fn$$

Eqn. 3.4: Meteorological Factor Calculation at Study Location

Where:

n = Number of dependent points / triangulation accuracy (n ≤ 6) (i.e. n = 0: study location; n = 1: closest known data point; n = 2: second closest known data point; …; n = 6: sixth closest known data point)

x_n = X co-ordinate of point n

y_n = Y co-ordinate of point n

d_n = Distance between study location and point n = $\sqrt{(x_0 - x_n)^2 + (y_0 - y_n)^2}$

f_n = Meteorological variable value at point n (variables include precipitation, temperature, relative humidity, wind direction proportions, etc.)

3.3.2. Land Use Data

The WS-LUR final model variables shown in Table 3.2 identified natural / agricultural land use as one of the key elements in determining the NO_2 concentration at a receptor point. The Co-Ordinated Information on the Environment (CORINE) land use mapping (European Environment Agency & Copernicus, 2020) was used to identify the areas of land categorised as agricultural or natural. CORINE mapping has been carried out by the EPA for the EEA on a six year basis since 2000, with the latest completed in 2018, and is part of a Europe-wide survey. Lands are divided into five main categories of artificial surfaces, agricultural, forest and semi-natural, wetlands and water bodies, which are also further divided into forty five sub-categories.

For the purposes of this study, the 2018 data was used and reduced to two categories, agricultural / natural and non-agricultural / non-natural, using the Reclassify tool in the ArcGIS 10.6 software, as shown in Figure 3.4. The Focal Statistics tool within the Neighbourhood function was used to create eight separate rasters representing each wind sector, as illustrated for the North sector in Figure 3.5. The Focal Statistics tool allows the modeller to specify the start and end angles of a sector as well as a radius to analyse the data in a raster map and then assigns the sum of the values located within that sector to the origin cell.

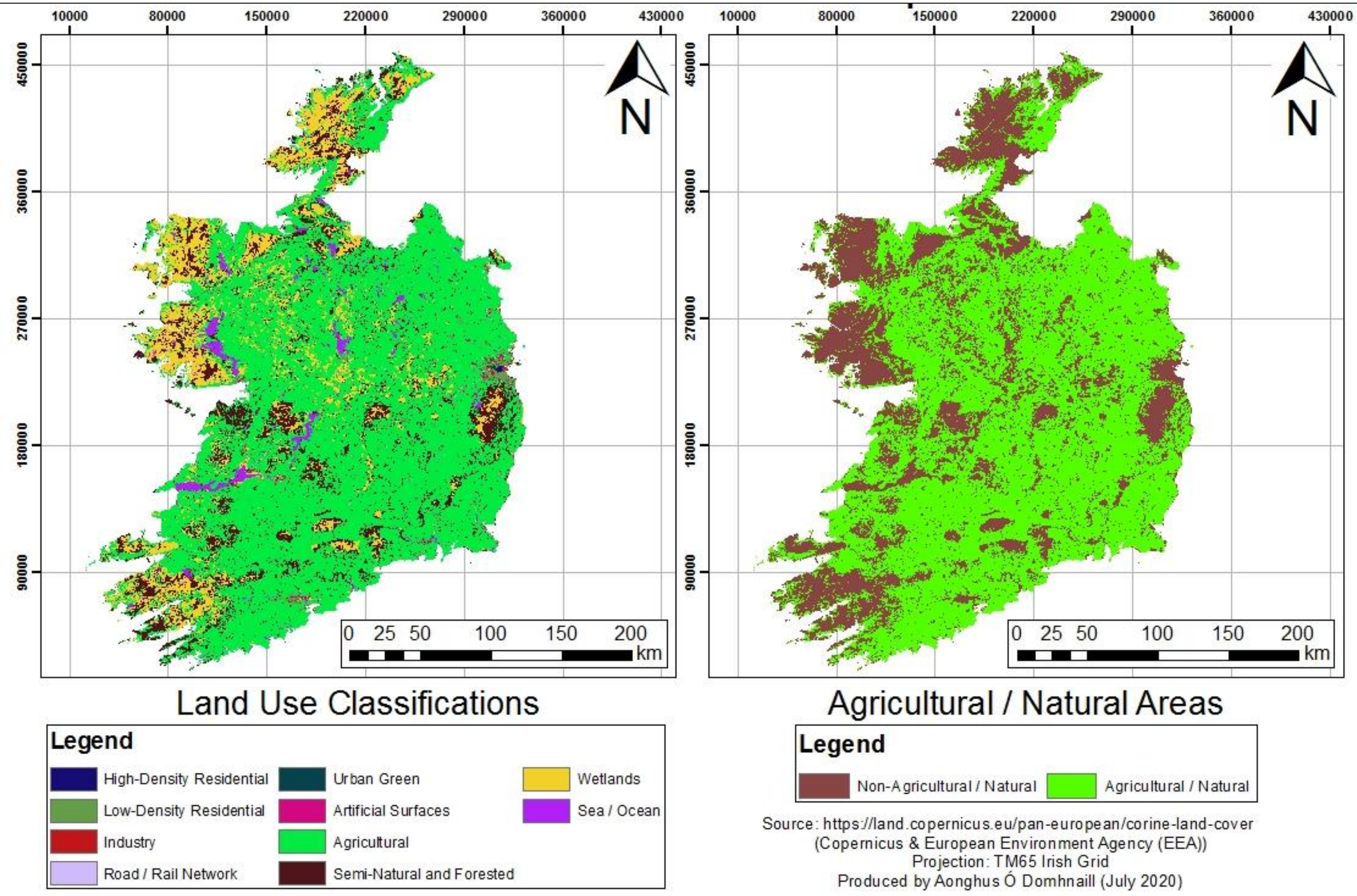


Figure 3.4: CORINE Land Use Maps (Data Source: European Environment Agency & Copernicus, 2020)

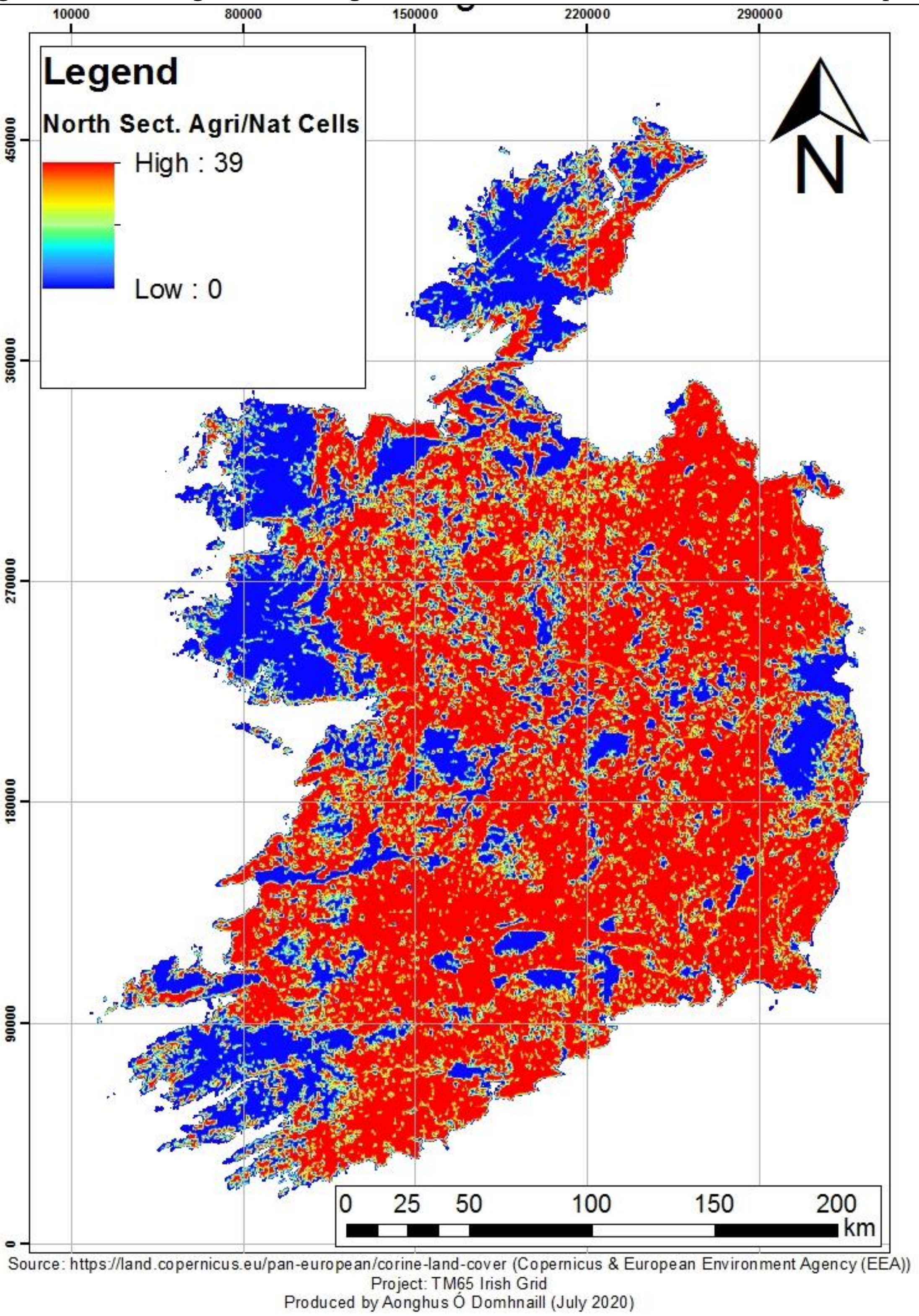
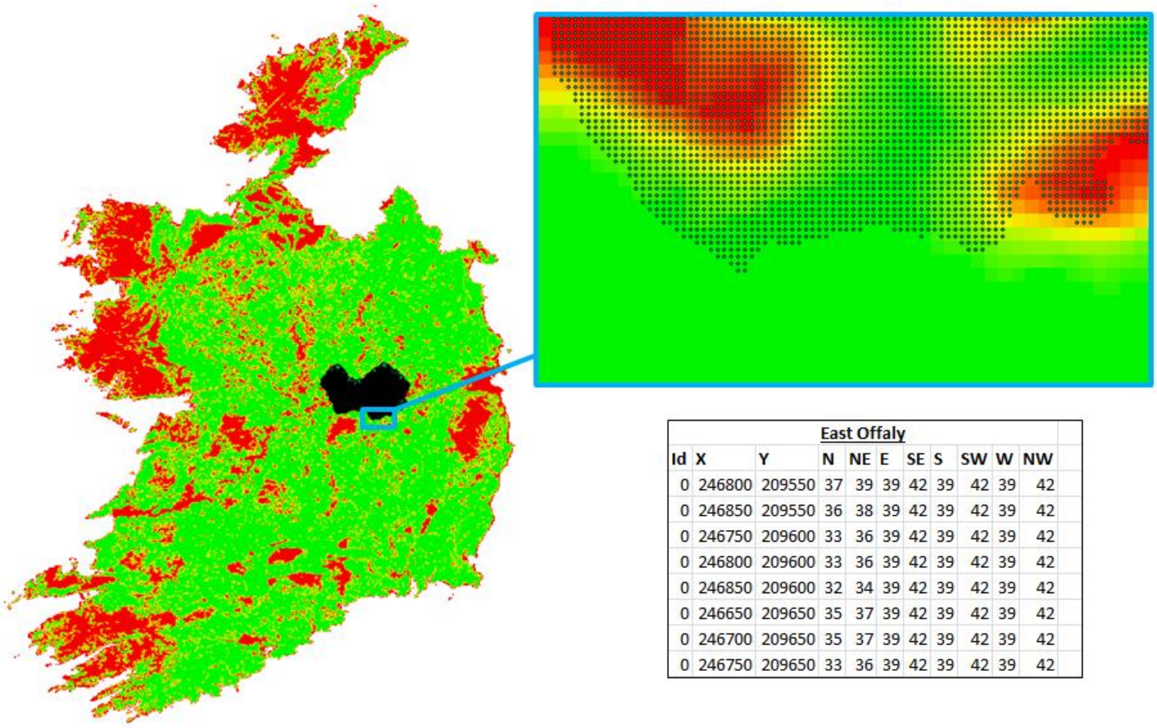


Figure 3.5: CORINE North Sector Agricultural / Natural Land Analysis (Data Source: European Environment Agency & Copernicus, 2020)

A 50 x 50 m grid of points was created, covering the entire country. Due to the limit on the number of rows of data in Excel (1 096 000 rows) the points file was broken down into regions of counties (e.g. North Cavan, South Cavan, etc.). The use of these reduced points files improved the processing time considerably when extracting values from the rasters to the grid points. The Extract Multi Values to Points tool in the Extraction function was used to add the values to the points in an Excel compatible format, as illustrated in Figure 3.6. The example shown is an extract on the border of East Offaly. This region is mainly categorised as agricultural land and therefore values achieved in this region are at the higher end of the scale, 32 – 42, which represents the number of agricultural cells within the sector. These values are greater than might be expected in areas located in close proximity to towns / cities or in coastal regions, which typically would have close to zero agricultural cells.



East Offaly										
Id	X	Y	N	NE	E	SE	S	SW	W	NW
0	246800	209550	37	39	39	42	39	42	39	42
0	246850	209550	36	38	39	42	39	42	39	42
0	246750	209600	33	36	39	42	39	42	39	42
0	246800	209600	33	36	39	42	39	42	39	42
0	246850	209600	32	34	39	42	39	42	39	42
0	246650	209650	35	37	39	42	39	42	39	42
0	246700	209650	35	37	39	42	39	42	39	42
0	246750	209650	33	36	39	42	39	42	39	42

Figure 3.6: Extract Multi Values to Points (Data Source: European Environment Agency & Copernicus, 2020)

Due to the large amount of data in each of these regions, separate summary sheets were prepared for each province, i.e. Connacht, Munster, etc. Once the coordinates of the study location match the coordinates of a point in one of the county regions, the summary table will confirm this and return the respective agricultural land use area for each wind sector, as shown in Figure 3.7. The reduced summary sheets reduced processing time as the Location Within County is an array formula that searches through numerous columns at once to check if the criterion is met.

Area / County	Location Within County	N	NE	E	SE	S	SW	W	NW
Ulster									
North Cavan	NO								
South Cavan	NO								
Central Donegal	NO								
North East Donegal	NO								
South Donegal	YES	39	42	39	25	38	42	39	42
West Donegal	NO								
East Monaghan	NO								
West Monaghan	NO								

Figure 3.7: Ulster Agricultural Land Use Summary Sheet (Data Source: European Environment Agency & Copernicus, 2020)

3.3.3. Commercial Properties Data

Data for commercial properties were retrieved from the EPA GIS Department and An Post / Geodirectory (GeoDirectory, 2020). The data is stored in an ArcGIS points file which contains data on buildings classified as commercial or both commercial and residential. The goal of this section of the analysis was to determine the number of commercial properties located within each directional sector for all points in the country. An example of an Excel compatible output using the Extract Multi Values to Points tool is shown in Figure 3.8. The Point Statistics tool within the Neighbourhood function of ArcGIS was used to analyse the data and generate eight separate rasters which assigned a value to each cell based on the number of points located within the specified sector start and end angles and sector radius. Figure 3.9 shows a map of the commercial properties points file which was used for this analysis and a raster generated using the Point Statistics tool which calculates the number of commercial properties within a specific sector direction. Information within these rasters was then transferred to an Excel spreadsheet, as described above, which identifies point coordinates and the related number of commercial properties in each directional sector. Summary sheets similar to those prepared for the Agricultural / Natural data, shown in Figure 3.7, were prepared for the Commercial Properties data, with the same Excel functions utilised to link the data to the model.

North Cavan

Id	X	Y	N	NE	E	SE	S	SW	W	NW
0	244000	298550	1	2	-9999	3	2	3	-9999	1
0	244050	298550	-9999	2	1	3	2	2	-9999	2
0	243850	298600	1	2	-9999	3	2	4	-9999	1
0	243900	298600	1	2	-9999	3	2	3	-9999	1
0	243950	298600	1	2	-9999	3	2	3	-9999	1
0	244000	298600	1	2	-9999	3	2	2	-9999	1
0	244050	298600	-9999	2	1	3	2	1	-9999	2
0	244100	298600	-9999	2	1	4	2	1	-9999	2
0	241000	298650	1	-9999	1	2	1	2	-9999	2
0	241050	298650	-9999	-9999	1	2	1	2	-9999	2
0	241100	298650	-9999	1	1	2	1	2	1	1
0	243800	298650	1	2	-9999	3	3	2	-9999	2
0	243850	298650	2	2	-9999	3	2	3	-9999	2
0	243900	298650	2	2	-9999	3	2	3	-9999	1
0	243950	298650	2	2	-9999	3	2	2	-9999	1
0	244000	298650	2	2	-9999	3	2	1	-9999	1

South Cavan

Id	X	Y	N	NE	E	SE	S	SW	W	NW
0	265850	280000	1	5	1	1	-9999	1	3	5
0	265750	280050	3	2	4	-9999	1	1	2	4
0	265800	280050	2	2	4	1	1	1	2	5
0	265850	280050	2	3	3	1	1	1	3	4
0	265900	280050	2	3	3	1	-9999	1	4	4
0	265650	280100	3	2	2	-9999	1	2	1	3
0	265700	280100	2	2	3	-9999	1	1	2	4
0	265750	280100	1	2	5	-9999	1	1	3	4
0	265800	280100	2	1	5	-9999	1	1	3	4
0	265850	280100	2	1	5	-9999	1	1	3	4
0	265900	280100	2	2	4	1	-9999	2	2	4
0	265950	280100	2	3	3	1	-9999	1	2	4
0	265600	280150	4	2	1	-9999	1	2	2	1
0	265650	280150	3	2	3	-9999	1	2	2	2
0	265700	280150	2	2	3	-9999	1	2	2	3
0	265750	280150	1	2	5	-9999	1	2	2	4

Figure 3.8: Example Commercial Properties Extracted Values Spreadsheet (Data Source: GeoDirectory, 2020)

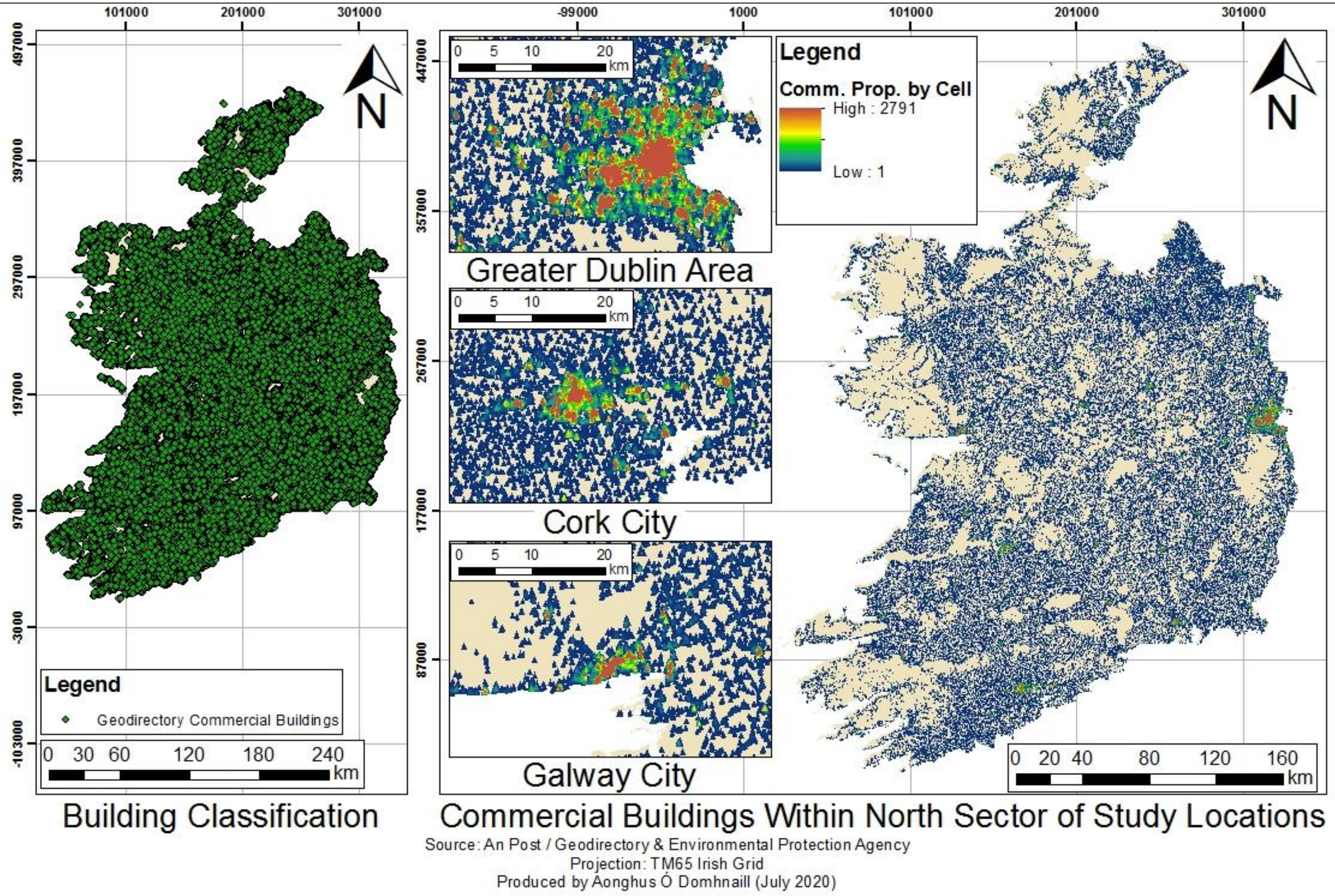


Figure 3.9: Geodirectory Commercial Properties Maps (Data Source: GeoDirectory, 2020)

3.3.4. Traffic Data

Road type data and traffic flows were obtained from the National Transport Model for 2016 (National Transport Authority, 2020). The data were limited to the east region of Ireland, which includes all of Leinster and counties Cavan and Monaghan. All route types (motorway, national, rural and local) are covered by the National Transport Model which provided data on traffic flows for various trip categories for all time periods (AM Peak, School Run, Lunch Time, Off Peak and PM Peak). The flow values for each trip category within these time periods were provided in terms of Passenger Car Units (PCUs) rather than vehicle numbers for each vehicle type. To account for this PCU factor, the flows in each time period were calculated using the following equations:

$$CAR_T = \sum_{i=1}^{6} F_i$$ **Eqn. 3.5: Passenger Car Flow for Time Period, T (National Transport Authority, 2020)**

$$LGV_T = \frac{F_7}{LGV_{PCU}}$$ **Eqn. 3.6: Light Goods Vehicles (LGV) Flow for Time Period, T (National Transport Authority, 2020)**

$$HDV_T = \frac{F_8}{OGV1_{PCU}} + \frac{\sum_{i=9}^{10} F_i}{OGV2_{PCU}}$$ **Eqn. 3.7: HDV Flow for Time Period, T (National Transport Authority, 2020)**

$$BUS_T = \frac{F_{11}}{BUS_{PCU}}$$ **Eqn. 3.8: Bus Flow for Time Period, T (National Transport Authority, 2020)**

Where:

V_T = Vehicle flow during time period, T

T = Time period (AM = AM peak, SR = school run, LT = lunch time, OP = Off peak, PM = PM peak)

$F_{i,}$ = Trip category (F_1 = car - employer's business, F_2 = car two-way commute, F_3 = car other, F_4 = car education, F_5 = car retired, F_6 = car taxi, F_7 = LGVs, F_8 = OGV1, F_9 = OGV2 with permit, F_{10} = OGV2 no permit, F_{11} = bus)

V_{PCU} = Passenger car unit factor for vehicle type, V (LGV_{PCU} = 1, $OGV1_{PCU}$ = 1.9, $OGV2_{PCU}$ = 2.5, BUS_{PCU} = 3)

LGVs = Goods vehicles less than 3.5 tonnes unladen weight

HDVs = Goods vehicles greater than 3.5 tonnes unladen weight

OGV1 = Ordinary goods vehicles with two / three axles

OGV2 = Ordinary goods vehicles with four or more axles (Includes OGV1 vehicles with trailers)

The original model developed to determine the NO_2 concentration at a specific location, employed the Annual Average Daily Traffic (AADT) on all routes to determine the Inverse Distance Weighted Vehicle Kilometres Travelled (IDWVKT) variable. The new model requires the AADT variable to be split by vehicle type (i.e. cars, LGVs, HDVs, etc.) so that emission weightings can be applied in the IDWVKT variable. To calculate the AADT of each vehicle type, the flows for each time period must be factored by applying a Period to Hour (PtH) Factor and combined as shown in Equation 3.9. The PtH factor is a weighting which can be utilised to determine the proportion of a full day that each of the time periods represent. The PtH Factor values shown under Equation 3.9 were all calculated based on the following methodology:

1. Observed 2-way flows for all routes for one hour within a time period as well as the observed 2-way flows for the three hours representing the time period were obtained from automatic traffic counters (ATC)
    - Time periods include:
        - **AM Peak:** flows for the time period between 07:00 and 10:00
        - **Lunch Time:** flows for the time period between 10:00 and 13:00
        - **School Run:** flows for the time period between 13:00 and 16:00
        - **PM Peak:** flows for the time period between 16:00 and 19:00
        - **Off Peak:** flows for the time period outside of the above hours (between 19:00 and 07:00)
2. Factors that translate observed one hour 2-way flows to observed three hour 2-way flows were calculated for all routes
3. Factors were flow weighted for all routes to determine a region wide PtH Factor for all routes for the specific time period
4. Methodology was repeated to determine the PtH Factor for all time periods

The total AADT was then calculated by adding all the AADT values for each vehicle type, as shown in Equation 3.10.

$$AADT_V = \frac{V_{AM}}{AM_{PtH}} + \frac{V_{SR}}{SR_{PtH}} + \frac{V_{LT}}{LT_{PtH}} + \frac{V_{PM}}{PM_{PtH}} + \frac{V_{OP}}{OP_{PtH}}$$

Eqn. 3.9: Vehicle AADT (National Transport Authority, 2020)

$$Total\ AADT = AADT_{CAR} + AADT_{LGV} + AADT_{HGV} + AADT_{BUS}$$

Eqn. 3.10: Total AADT (National Transport Authority, 2020)

Where:

$AADT_V$ = Annual average daily traffic for vehicle type, V

T_{PtH} = Period to hour factor (AM_{PtH} = 0.352, SR_{PtH} = 0.362, LT_{PtH} = 0.343, OP_{PtH} = 0.152, PM_{PtH} = 0.346)

The traffic data was initially available as separate ArcGIS line files for each time period, containing flow data in terms of PCUs. The calculations above were carried out within ArcGIS to create a single line shapefile which contains the AADT values for each vehicle type and a total AADT value for every route. As the data is contained in a line file, typically the Line Statistics tool within the Neighbourhood function would be used to analyse the data and determine the number of vehicle kilometres travelled at each location. However, the Line Statistics tool is limited as it cannot analyse the data by sectors around a point, instead it analyses the entire area within a radius of a point. Therefore, the line file was changed to a point file to allow the Point Statistics tool to be used instead. This was achieved using the Feature to Line tool within the Features function of ArcGIS, which generated points at the midpoints of all line sections and transferred all data (Vehicle Type AADT and Total AADT values) from the lines to the corresponding points. The length of line represented by each of the points was also transferred across to the points file. The number of vehicle kilometres travelled by each vehicle type was calculated by multiplying the length of line by the AADT for each vehicle type, as shown in Equation 3.11.

$$VKT_V = AADT_V \; x \; Length \; of \; Route$$ **Eqn. 3.11: Vehicle AADT Formula**

Where:

VKT_V = Vehicle kilometres travelled by vehicle type, V

Length of Route = Section of route where AADT is applicable (typically this represents the link between two intersections on the route)

Once this was completed, the Point Statistics tool was used to generate rasters representing each of the Vehicle Type VKTs within the wind direction sectors and radii specified in Table 3.2. An example of an output raster for Vehicle VKT is shown in Figure 3.10. A similar approach was used to determine the statistics for the road density variable within each wind directional sector, which focused only on the length of the routes within 0.25 km of a study location, as specified in Table 3.2.

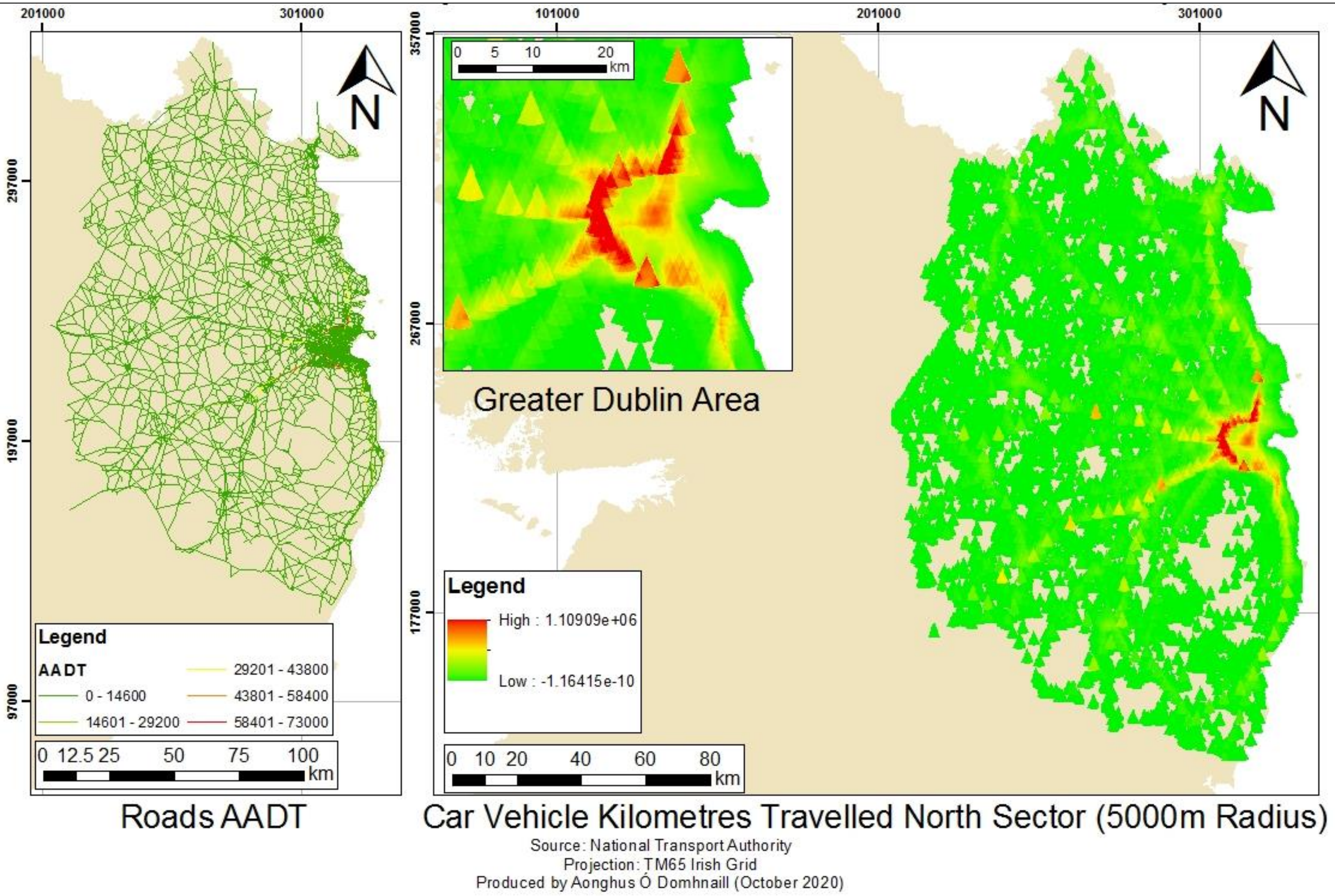


Figure 3.10: NTA Road Density and Vehicle Kilometres Travelled Maps (Data Source: National Transport Authority, 2020)

The distance weighting was then applied to the VKT to calculate the IDWVKT value at all points. This was completed using the Raster Calculator tool within the Map Algebra function of ArcGIS. The following formula was used to combine the rasters in Map Algebra and generate individual rasters for every vehicle type in every wind direction sector:

$$IDWVKT_V = {}^{1}/_{d_i}\left(VKT_{V,i}\right) + {}^{1}/_{d_{i+1}}\left(VKT_{V,i+1} - VKT_{V,i}\right) + \cdots + {}^{1}/_{d_{n-1}}\left(VKT_{V,n-1} - VKT_{V,n-2}\right) + {}^{1}/_{d_n}\left(VKT_{V,n} - VKT_{V,n-1}\right)$$

Eqn. 3.12: IDWVKT Formula (Naughton et al., 2018)

Where:

$IDWVKT_V$ = Inverse distance weighted vehicle kilometres travelled for vehicle type, V

d_i = Distance to receptor location

3.3.5. Vehicle Breakdown Analysis

In this section of the analysis, the breakdowns of the vehicle fleet for each of the pre-set years in the model and the original study period, 2010 – 2012, were calculated and from these data the average NO_2 emitted by a vehicle in each time period was calculated. This average emission value was used to determine the NO_2 emission weighting of every vehicle type / Euro Class and alter the IDWVKT variable in the WS-LUR model formula. This process begins by analysing data from the Irish Bulletin of Vehicle and Driver Statistics by the Department of Transport, Tourism and Sport (Department of Transport, Tourism and Sport, 2011; Department of Transport, Tourism and Sport, 2012; Department of Transport, Tourism and Sport, 2013; Department of Transport, Tourism and Sport, 2014; Department of Transport, Tourism and Sport, 2015; Department of Transport, Tourism and Sport, 2016; Department of Transport, Tourism and Sport, 2017; Department of Transport, Tourism and Sport, 2018; Department of Transport, Tourism and Sport, 2019) and the Air Pollutant Emission Inventory Guidebook by the EMEP/EEA (European Environment Agency, 2019) described in Section 3.2. Details of the fuel type, unladen weights, engine capacities and year when first licensed were available in the Irish Bulletin of Vehicle and Driver Statistics to determine the Euro Class breakdown of each vehicle category (i.e. Passenger Cars, LGVs, HDVs, etc.) as shown in the flow diagram in Figure 3.11.

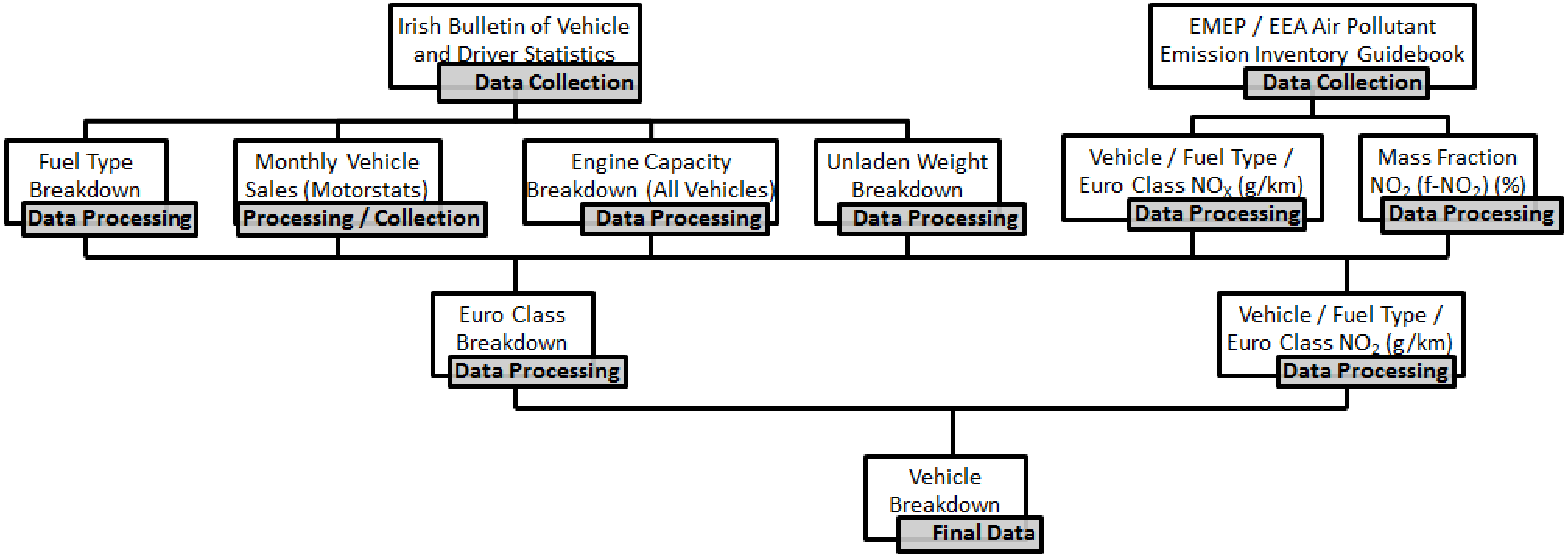


Figure 3.11: Vehicle Breakdown Analysis Flow Diagram

Table 3.3 below identifies the abbreviations used for various elements (vehicle type, fuel type, etc.) in notations within tables and formulas within this section and subsequent sections of the thesis.

Table 3.3: Vehicle Breakdown Analysis Abbreviations

	Abbreviation		**Abbreviation**
All Euro Classes	*A*	**Fuel Type**	*f*
Buses (Compressed Natural Gas)	*BC*	**Fuel Type Percentage**	$F_{v,f}$
Buses (Standard)	*BS*	**Hybrid Petrol**	*H*
Compressed Natural Gas	*C*	**Heavy Duty Vehicles**	*HDV*
Conventional	*CN*	**Hybrid Petrol Large**	*HPL*
Buses (Coaches Standard)	*CS*	**Hybrid Petrol Medium**	*HPM*
Diesel	*D*	**Hybrid Petrol Small**	*HPS*
Diesel Large	*DL*	**Light Commercial Vehicles**	*LCV*
Diesel Medium	*DM*	**Liquefied Petroleum Gas**	*LPG*
Diesel >32 tonnes	*DMAX*	**Large Public Service Vehicles**	*LPSV*
Diesel Small	*DS*	**Motorcycles**	*M*
Diesel 7.5 – 16 tonnes	*D16*	**Moped Euro Class**	*Mop*
Diesel 16 – 32 tonnes	*D32*	**Motorcycle Euro Class**	*Mot*
Diesel <7.5 tonnes	*D7.5*	**Group Number**	*n*
Euro Class	*e*	**Open Loop**	*OL*
Ethanol E85	*E*	**Petrol**	*P*
Engine Capacity Percentage	$E_{v,s}$	**Passenger Cars**	*PC*
Euro II	*EII*	**Pre-ECE Euro Class**	*PECE*
Euro III	*EIII*	**Petrol Large**	*PL*
Euro IV	*EIV*	**Petrol Medium**	*PMED*
Estimated Euro Class Percentage	$EC_{v,y,e}$	**Petrol Mini**	*PMIN*
Euro V	*EV*	**Pre-Euro** **Pre-Euro / Euro 1** **Pre-Euro / Euro I** **Pre-Euro / Euro 1 / Euro 2** **Pre-Euro / Euro I / Euro II**	*PRE*
Pre-Euro Class (ECE 15/00-01)	*ECE1*	**Petrol Small**	*PS*
Pre-Euro Class (ECE 15/02)	*ECE2*	**Small Public Service Vehicles**	*SPSV*
Pre-Euro Class (ECE 15/03)	*ECE3*	**Vehicle Sub-Type Euro Class Percentage**	$T_{v,s,n,e}$
Pre-Euro Class (ECE 15/04)	*ECE4*	**Unladen Weight Percentage**	$U_{v,s}$

	Abbreviation		Abbreviation
Enhanced Environmentally Friendly Vehicle	*EEV*	**Vehicle Type**	v
Euro VI	*EVI*	**Vehicle Sub-Type Percentage**	v_S
Euro 1	*E1*	**Calculated Euro Class Percentage**	$v_{S,e}$
Euro 2	*E2*	**Vehicle Type Percentage**	V_V
Euro 3	*E3*	**Weighting Factor Percentage**	W_V
Euro 4	*E4*	**Year / Time Period**	y
Euro 4 and Later	*E4&L*	**2-Stroke >50cm^3**	*2S-MAX*
Euro 5	*E5*	**2-Stroke <50cm^3**	*2S-50*
Euro 6	*E6*	**2010 - 2012**	*2010-12*
Euro 6 (≤2016)	*E6-2016*	**4-Stroke >750cm^3**	*4S-MAX*
Euro 6 (≤2017)	*E6-2017*	**4-Stroke <250cm^3**	*4S-250*
Euro 6 (2017 – 2019)	*E6-2019*	**4-Stroke <50cm^3**	*4S-50*
Euro 6 (2018 – 2020)	*E6-2020*	**4-Stroke 250 - 750cm^3**	*4S-750*

An Estimated Euro Class Breakdown was calculated for every vehicle type based on the year of first registration data from the Irish Bulletin of Vehicle and Driver Statistics (Department of Transport, Tourism and Sport, 2019; Department of Transport, Tourism and Sport, 2018; Department of Transport, Tourism and Sport, 2017; Department of Transport, Tourism and Sport, 2013; Department of Transport, Tourism and Sport, 2012; Department of Transport, Tourism and Sport, 2011) for all vehicle types (cars and goods vehicles). Most of the Euro Classes were introduced on the first day of a year but in some cases they were introduced in a specific month of the year. Details of the breakdown by month were not included in the year of first registration data and therefore the Motorstats database (Motorstats, 2020) was utilised to determine the trends in vehicle (cars, LGVs and HDVs) registrations on a month by month basis for every year. Table 3.4, Table 3.5, Table 3.6 and Table 3.7 show the Euro Classes which were applicable for all vehicle types during each of the study years / periods. The notation systems used in the tables are presented below each table.

Table 3.4: Passenger Cars (PCs) / Small Public Service Vehicles (SPSVs) Estimated Euro Class Breakdown

EURO CLASSIFICATION (e)	PASSENGER CARS (PCs) / SMALL PUBLIC SERVICE VEHICLES (SPSVs) ESTIMATED EURO CLASS BREAKDOWN % *(ECv,y,e)*			
	PERIOD / YEAR (y)			
	2010 - 2012	**2016**	**2017**	**2018**
Euro 6 (2017 - 2019)	-	-	$EC_{PC,2017,E6\text{-}2019}$ / $EC_{SPSV,2017,E6\text{-}2019}$	$EC_{PC,2018,E6\text{-}2019}$ / $EC_{SPSV,2018,E6\text{-}2019}$
Euro 6 (≤2016)	-	$EC_{PC,2016,E6\text{-}2016}$ / $EC_{SPSV,2016,E6\text{-}2016}$	$EC_{PC,2017,E6\text{-}2016}$ / $EC_{SPSV,2017,E6\text{-}2016}$	$EC_{PC,2018,E6\text{-}2016}$ / $EC_{SPSV,2018,E6\text{-}2016}$
Euro 5	$EC_{PC,2010\text{-}12,E5}$ / $EC_{SPSV,2010\text{-}12,E5}$	$EC_{PC,2016,E5}$ / $EC_{SPSV,2016,E5}$	$EC_{PC,2017,E5}$ / $EC_{SPSV,2017,E5}$	$EC_{PC,2018,E5}$ / $EC_{SPSV,2018,E5}$
Euro 4	$EC_{PC,2010\text{-}12,E4}$ / $EC_{SPSV,2010\text{-}12,E4}$	$EC_{PC,2016,E4}$ / $EC_{SPSV,2016,E4}$	$EC_{PC,2017,E4}$ / $EC_{SPSV,2017,E4}$	$EC_{PC,2018,E4}$ / $EC_{SPSV,2018,E4}$
Euro 3	$EC_{PC,2010\text{-}12,E3}$ / $EC_{SPSV,2010\text{-}12,E3}$	$EC_{PC,2016,E3}$ / $EC_{SPSV,2016,E3}$	$EC_{PC,2017,E3}$ / $EC_{SPSV,2017,E3}$	$EC_{PC,2018,E3}$ / $EC_{SPSV,2018,E3}$
Euro 2	$EC_{PC,2010\text{-}12,E2}$ / $EC_{SPSV,2010\text{-}12,E2}$	-	-	-
Pre-Euro / Euro 1 / Euro 2	-	$EC_{PC,2016,PRE}$	$EC_{PC,2017,PRE}$	$EC_{PC,2018,PRE}$
Pre-Euro / Euro 1	$EC_{PC,2010\text{-}12,PRE}$ / $EC_{SPSV,2010\text{-}12,PRE}$	-	-	-

Where:

$EC_{PC,y,E6\text{-}2019}$ / $EC_{SPSV,y,E6\text{-}2019}$ = % of vehicles first registered between 1st Jan '17 and 31st Dec '19

$EC_{PC,y,E6\text{-}2016}$ / $EC_{SPSV,y,E6\text{-}2016}$ = % of vehicles first registered between 1st Sept '15 and 31st Dec '16

$EC_{PC,y,E5}$ / $EC_{SPSV,y,E5}$ = % of vehicles first registered between 1st Jan '11 and 31st Aug '15

$EC_{PC,y,E4}$ / $EC_{SPSV,y,E4}$ = % of vehicles first registered between 1st Jan '06 and 31st Dec '10

$EC_{PC,y,E3}$ / $EC_{SPSV,y,E3}$ = % of vehicles first registered between 1st Jan '01 and 31st Dec '05

$EC_{PC,y,E2}$ / $EC_{SPSV,y,E2}$ = % of vehicles first registered between 1st Jan '97 and 31st Dec '00

$EC_{PC,y,PRE}$ / $EC_{SPSV,y,PRE}$ = % of vehicles first registered prior to 1st Jan '97

Table 3.5: Light Commercial Vehicles (LCVs) Estimated Euro Class Breakdown

LIGHT COMMERCIAL VEHICLES (LCV) ESTIMATED EURO CLASS BREAKDOWN % ***(ECv,y,e)***					
		PERIOD / YEAR (y)			
		2010 - 2012	**2016**	**2017**	**2018**
EURO CLASSIFICATION *(e)*	Euro 6 (2018 - 2020)	-	-	-	$EC_{LCV,2018,E6\text{-}2020}$
	Euro 6 (≤2017)	-	$EC_{LCV,2016,E6\text{-}2017}$	$EC_{LCV,2017,E6\text{-}2017}$	$EC_{LCV,2018,E6\text{-}2017}$
	Euro 5	$EC_{LCV,2010\text{-}12,E5}$	$EC_{LCV,2016,E5}$	$EC_{LCV,2017,E5}$	$EC_{LCV,2018,E5}$
	Euro 4	$EC_{LCV,2010\text{-}12,E4}$	$EC_{LCV,2016,E4}$	$EC_{LCV,2017,E4}$	$EC_{LCV,2018,E4}$
	Euro 3	$EC_{LCV,2010\text{-}12,E3}$	$EC_{LCV,2016,E3}$	$EC_{LCV,2017,E3}$	$EC_{LCV,2018,E3}$
	Euro 2	$EC_{LCV,2010\text{-}12,E2}$	-	-	-
	Pre-Euro / Euro 1 / Euro 2	-	$EC_{LCV,2016,PRE}$	$EC_{LCV,2017,PRE}$	$EC_{LCV,2018,PRE}$
	Pre-Euro / Euro 1	$EC_{LCV,2010\text{-}12,PRE}$	-	-	-

Where:

$EC_{LCV,y,E6\text{-}2020}$ = % of vehicles first registered between 1st Jan '18 and 31st Dec '20

$EC_{LCV,y,E6\text{-}2017}$ = % of vehicles first registered from 1st Sept '15 for unladen weight ≤1305kg and from 1st Sept '16 for unladen weight >1305kg to 31st Dec '17

$EC_{LCV,y,E5}$ = % of vehicles first registered between 1st Jan '11 and 31st Aug '15 for unladen weight ≤1305kg, between 1st Jan '12 and 31st Aug '16 for unladen weight between 1306kg and 1760kg, between 1st Jan '13 and 31st Aug '16 for unladen weight >1760kg

$EC_{LCV,y,E4}$ = % of vehicles first registered between 1st Jan '06 and 31st Dec '10 for unladen weight ≤1305kg, between 1st Jan '07 and 31st Dec '11 for unladen weight between 1306kg and 1760kg and between 1st Jan '07 and 31st Dec '12 for unladen weight >1760kg

$EC_{LCV,y,E3}$ = % of vehicles first registered between 1st Jan '01 and 31st Dec '05 for unladen weight ≤1305kg and between 1st Jan '02 and 31st Dec '06 for unladen weight >1305kg

$EC_{LCV,y,E2}$ = % of vehicles first registered between 1st Oct '97 and 31st Dec '00 for unladen weight ≤1305kg, between 1st Jan '98 and 31st Dec '01 for unladen weight between 1306kg and 1760kg and between 1st Jan '99 and 31st Dec '01 for unladen weight >1760kg

$EC_{LCV,y,PRE}$ = % of vehicles first registered prior to start dates of Euro class 2

Table 3.6: Heavy Duty Vehicles (HDVs) Estimated Euro Class Breakdown

HEAVY DUTY VEHICLES (HDVs) / LARGE PUBLIC SERVICE VEHICLES (LPSVs) ESTIMATED EURO CLASS BREAKDOWN % *(ECv,y,e)*					
		PERIOD / YEAR (y)			
		2010 - 2012	**2016**	**2017**	**2018**
EURO CLASSIFICATION (e)	Euro VI	-	$EC_{HDV,2016,EVI}$ / $EC_{LPSV,2016,EVI}$	$EC_{HDV,2017,EVI}$ / $EC_{LPSV,2017,EVI}$	$EC_{HDV,2018,EVI}$ / $EC_{LPSV,2018,EVI}$
	Euro V	$EC_{HDV,2010-12,EV}$ / $EC_{LPSV,2010-12,EV}$	$EC_{HDV,2016,EV}$ / $EC_{LPSV,2016,EV}$	$EC_{HDV,2017,EV}$ / $EC_{LPSV,2017,EV}$	$EC_{HDV,2018,EV}$ / $EC_{LPSV,2018,EV}$
	Euro IV	$EC_{HDV,2010-12,EIV}$ / $EC_{LPSV,2010-12,EIV}$	$EC_{HDV,2016,EIV}$ / $EC_{LPSV,2016,EIV}$	$EC_{HDV,2017,EIV}$ / $EC_{LPSV,2017,EIV}$	$EC_{HDV,2018,EIV}$ / $EC_{LPSV,2018,EIV}$
	Euro III	$EC_{HDV,2010-12,EIII}$ / $EC_{LPSV,2010-12,EIII}$	$EC_{HDV,2016,EIII}$ / $EC_{LPSV,2016,EIII}$	$EC_{HDV,2017,EIII}$ / $EC_{LPSV,2017,EIII}$	$EC_{HDV,2018,EIII}$ / $EC_{LPSV,2018,EIII}$
	Euro II	$EC_{HDV,2010-12,EII}$ / $EC_{LPSV,2010-12,EII}$	-	-	-
	Pre-Euro / Euro I / Euro II	-	$EC_{HDV,2016,PRE}$ / $EC_{LPSV,2016,PRE}$	$EC_{HDV,2017,PRE}$ / $EC_{LPSV,2017,PRE}$	$EC_{HDV,2018,PRE}$ / $EC_{LPSV,2018,PRE}$
	Pre-Euro / Euro I	$EC_{HDV,2010-12,PRE}$ / $EC_{LPSV,2010-12,PRE}$	-	-	-

Where:

$EC_{HDV,y,EVI}$ / $EC_{LPSV,y,EVI}$ = % of vehicles first registered from 1st Jan '13 onwards

$EC_{HDV,y,EV}$ / $EC_{LPSV,y,EV}$ = % of vehicles first registered between 1st Jan '08 and 31st Dec '12

$EC_{HDV,y,EIV}$ / $EC_{LPSV,y,EIV}$ = % of vehicles first registered between 1st Jan ‘05 and 31st Dec ‘07

$EC_{HDV,y,EIII}$ / $EC_{LPSV,y,EIII}$ = % of vehicles first registered between 1st Jan ‘00 and 31st Dec ‘04 (from 1st Jan ‘99 for enhanced environmentally friendly vehicle (EEVs))

$EC_{HDV,y,EII}$ / $EC_{LPSV,y,EII}$ = % of vehicles first registered between 1st Jan ‘97 and 31st Dec ‘99

$EC_{HDV,y,PRE}$ / $EC_{LPSV,y,PRE}$ = % of vehicles first registered prior to start dates of Euro class II

Table 3.7: Motorcycles (M) Estimated Euro Class Breakdown

MOTORCYCLES (M) ESTIMATED EURO CLASS BREAKDOWN % *($EC_{v,y,e}$)*					
		PERIOD / YEAR (y)			
		2010 - 2012	**2016**	**2017**	**2018**
EURO CLASSIFICATION *(e)*	Euro 3	$EC_{M,2010\text{-}12,E3}$	$EC_{M,2016,E3}$	$EC_{M,2017,E3}$	$EC_{M,2018,E3}$
	Euro 2	$EC_{M,2010\text{-}12,E2}$	$EC_{M,2016,E2}$	$EC_{M,2017,E2}$	$EC_{M,2018,E2}$
	Euro 1	$EC_{M,2010\text{-}12,E1}$	$EC_{M,2016,E1}$	-	-
	Pre-Euro / Euro 1	-	-	$EC_{M,2017,PRE}$	$EC_{M,2018,PRE}$
	Pre-Euro	$EC_{M,2010\text{-}12,PRE}$	$EC_{M,2016,PRE}$	-	-

Where:

$EC_{M,y,E3}$ = % of vehicles first registered after 1st July ‘07

$EC_{M,y,E2}$ = % of motorcycles first registered between 1st July ‘05 and 31st June ‘07, % of three-wheelers first registered between 1st July ‘04 and 31st June ‘07 and % of mopeds approved between 17th June ‘02 and 31st June ‘07

$EC_{M,y,E1}$ = % of vehicles approved between 17th June ‘99 and Euro class 2 start dates

$EC_{M,y,PRE}$ = % of vehicles approved prior to Euro class 1 start date

Equation 3.13 confirms that all vehicles within a specific vehicle type category are contained within one of these Euro Classes.

$$\sum EC_{v,2010-12,e} = \sum EC_{v,2016,e} = \sum EC_{v,2017,e} = \sum EC_{v,2018,e} = 100\%$$

Eqn. 3.13: Estimated Euro Class Breakdown

Where:

$EC_{v,2016,e}$ = % of vehicles in Euro class, e for vehicle type, v in period / year, y

The next step in the vehicle breakdown analysis was to calculate the above Estimated Euro Class breakdowns for each vehicle type using a number of variables such as the vehicle types, fuel types, vehicle sub-types, engine capacities and unladen weights data from the Irish Bulletin of Vehicle and Driver Statistics (Department of Transport, Tourism and Sport, 2019; Department of Transport, Tourism and Sport, 2018; Department of Transport, Tourism and Sport, 2017; Department of Transport, Tourism and Sport, 2016; Department of Transport, Tourism and Sport, 2015; Department of Transport, Tourism and Sport, 2014; Department of Transport, Tourism and Sport, 2013; Department of Transport, Tourism and Sport, 2012; Department of Transport, Tourism and Sport, 2011). This Euro Class breakdown will be known as the Calculated Euro Class breakdown in all future references. Equation 3.14 presents the equation used to determine the Calculated Euro Class breakdown of the fleet in each of the study years / periods.

$$V_v \; x \; F_{v,f} \; x \; E_{v,s} \; x \; U_{v,s} \; x \; W_v = v_s = \sum v_{s,e}$$

Eqn. 3.14: Vehicle Sub-Type Breakdown

Where:

V_v = % of total vehicles of which vehicle type, v

$F_{v,f}$ = % of vehicle type, v of which fuel type, f

$E_{v,s}$ = % of sub-type, s within engine capacity range of vehicle type, v (only applicable when vehicle type is dependent on engine capacity)

$U_{v,s}$ = % of sub-type, s within unladen weight range of vehicle type, v (only applicable when vehicle type is dependent on unladen weight)

W_v = Weighting factor for sub-types in vehicle type, v (only required when percentage specified in Irish Bulletin of Vehicle and Driver Statistics is applicable to multiple sub-types)

v_s = % of vehicle type, v of which sub-type, s

$v_{s,e}$ = % of vehicles in Euro class, e of sub-type, s of vehicle type, v

Equations 3.15 and 3.16 identify the calculation of Euro Class breakdowns of vehicle sub-types.

$$\sum T_{v,s,n,e} = 100\%$$ **Eqn. 3.15: Vehicle Sub-Type Euro Class Breakdown 1**

$$T_{v,s,n,e}\ x\ v_s = v_{s,e}$$ **Eqn. 3.16: Vehicle Sub-Type Euro Class Breakdown 2**

Where:

$T_{v,s,n,e}$ = % of vehicles in Euro Class, e which are classed as vehicle type, v, sub-type, s and group number, n (i.e. $\sum T_{PC,PMIN,2,e} = \sum T_{PC,PS,1,e} = \sum T_{PC,PMED,1,e} = \sum T_{PC,PL,1,e} = \sum T_{PC,DS,2,e} = \sum T_{PC,DM,1,e} = \sum T_{PC,DL,1,e} = \sum T_{PC,LPG,1,e} = \sum T_{PC,E,2,e} = \sum T_{PC,C,2,e} = 100\%$)

The only variable which was unknown and could not be sourced were the vehicle sub-type breakdowns by Euro Class ($T_{v,s,n,e}$). A vehicle sub-type defines the engine capacities or unladen weights of a vehicle type. The unladen weights are applicable to goods vehicle (LCVs and HDVs) sub-types whilst the engine capacities apply to all other vehicle types (Passenger Cars, Small Public Service Vehicles and Motorcycles). Therefore, it was assumed that the vehicle sub-type Euro class breakdown ($T_{v,s,n,e}$) was the same for all sub-types of a vehicle type except in the case of Passenger Cars, HDVs and Small Public Service Vehicles where there were two groups:

1. Vehicle Sub-Types which contain all Euro Class types from Pre-Euro to Euro 6
2. Vehicle Sub-Types which were only introduced from Euro 4 onwards

In the absence of data on the Euro Class breakdowns within each vehicle sub-type ($T_{v,s,n,e}$) group it was assumed that the percentage for a Euro Class was the same for all sub-types within the same group of a vehicle type, as shown in Equation 3.17.

Assumption: $T_{v,s,n,e} = T_{v,s+1,n,e} = T_{v,s+\cdots,n,e} = \cdots$ **Eqn. 3.17: Equal Euro Class Breakdown in Groups**

i.e. $T_{PC,PS,1,E4} = T_{PC,PMED,1,E4} = T_{PC,PL,1,E4} = T_{PC,DM,1,E4} = T_{PC,DL,1,E4} = T_{PC,LPG,1,E4}$

The vehicle sub-type Euro Class breakdowns ($T_{v,s,n,e}$) for vehicle types with two groups were calculated using Equations 3.18 and 3.19. The process used to determine the vehicle sub-type Euro Class breakdowns ($T_{v,s,n,e}$) for vehicle types with two groups is described in full in Section 3.3.5.1.

$$S_A P_{1,e} + S_{E4\&L} P_{2,e} = EC_{v,y,e}$$ **Eqn. 3.18: Vehicle Sub-Type Euro Class Breakdown Percentage 1**

$$P_{1,e} = {EC_{v,y,e} - S_{E4\&L} P_{2,e}} \big/ {S_A}$$ **Eqn. 3.19: Vehicle Sub-Type Euro Class Breakdown Percentage 2**

Where:

S_A = % of vehicles categorised as vehicle type, v and a sub-type in group 1

$S_{E4\&L}$ = % of vehicles categorised as vehicle type, v and a sub-type in group 2

$P_{1,e} = T_{v,s,n,e}$ = vehicle sub-type Euro Class % (for sub-types in group 1) (The sum of x (all Euro Classes) for a sub-type is equal to 100%)

$P_{2,e} = T_{v,s,n,e}$ = vehicle sub-type Euro Class % (for sub-types in group 2) (The sum of y (all Euro Classes) for a sub-type is equal to 100%)

The sum of the percentages for a specific Euro Class in each of the sub-types of a particular vehicle type using the Calculated Euro Class breakdown approach should be approximately equal to the percentage of the same Euro Class in the Estimated Euro Class breakdown approach, as shown in Equation 3.20.

$$\sum PC_{S,e} \approx EC_{PC,y,e}$$ **Eqn. 3.20: Calculated and Estimated Euro Class Breakdowns**

Calculated Euro Class Breakdown ≈ Estimated Euro Class Breakdown

Where:

The sum of the percentages for Euro Class, e in all sub-types of vehicle type, v is approximately equal to the estimated percentage for Euro Class, e in year y
(i.e. In 2016: $\sum PC_{s,E4} \approx EC_{PC,2016,E4}$)

Table 3.8 identifies all annotations used for all variables (fuel type percentages, vehicle sub-type percentages, engine capacity percentages, unladen weight percentages, group numbers, vehicle sub-type Euro Class percentages, weighting factor percentages and Euro Class percentages) for passenger cars within the vehicle breakdown analysis. Tables identifying annotations for all variables for other vehicle types (LCVs, HDVs, LPSVs, Motorcycles and SPSVs) are provided in Appendix A. All tables are structured in a way that the variables required to calculate the Euro Class percentages for a particular category can be easily sourced as they are separated by horizontal borders, as shown by the example for Euro 4 Petrol Mini Passenger Cars in Equation 3.21 and Figure 3.12.

$$PC_{PMIN,E4} = V_{PC} \ x \ F_{PC,P} \ x \ E_{PC,PMIN} \ x \ T_{PC,PMIN,2,E4}$$ **Eqn. 3.21: Euro 4 Petrol Mini Passenger Cars**

Where:

$PC_{PMIN,E4}$ = % of total vehicles categorised as Euro 4 petrol mini passenger cars

V_{PC} = % of total vehicles categorised as passenger cars

$F_{PC,P}$ = % of passenger cars fuelled by petrol

$E_{PC,PMIN}$ = % of petrol passenger cars with engine capacity within mini range (<1000 c.c.)

$T_{PC,PMIN,2,E4}$ = % of petrol mini passenger cars categorised as Euro 4

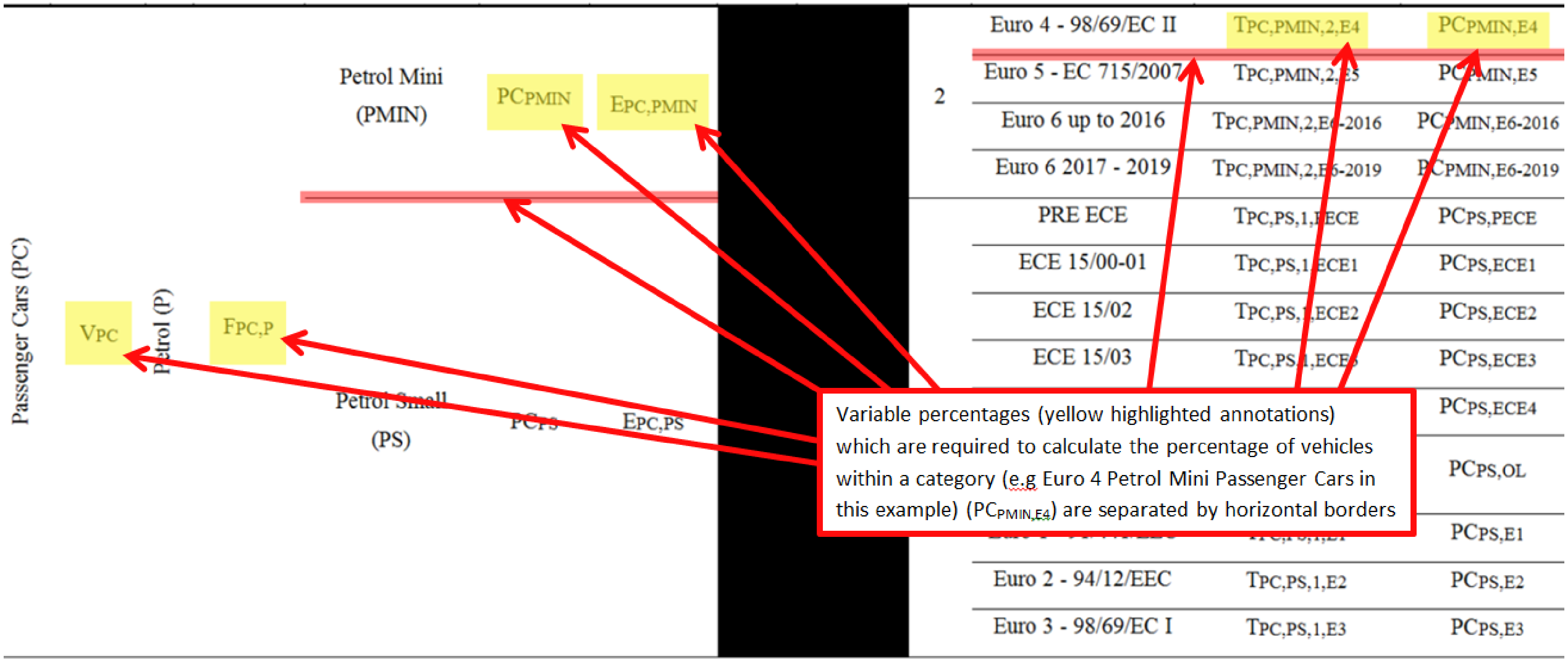


Figure 3.12: Euro 4 Petrol Mini Passenger Cars Percentage

Table 3.8: Passenger Cars (PC) Vehicle Breakdown Analysis and Annotations

VEHICLE TYPE (*v*)	VEHICLE TYPE % (V_v)	FUEL TYPE (*f*)	FUEL TYPE % ($F_{v,f}$)	VEHICLE SUB-TYPE (ENGINE CAPACITY CATEGORY OR UNLADEN WEIGHT CATEGORY) (*s*)	VEHICLE SUB-TYPE % (v_s)	ENGINE CAPACITY % ($E_{v,s}$)	UNLADEN WEIGHT % ($U_{v,s}$)	WEIGHTING FACTOR % (W_v)	GROUP NUMBER (*n*)	EURO CLASSIFICATION (*e*)	VEHICLE SUB-TYPE BREAKDOWN BY EURO CLASS % ($T_{v,s,n,e}$)	EURO CLASS % ($v_{s,e}$)
Passenger Cars (PC)	V_{PC}	Petrol (P)	$F_{PC,P}$	Petrol Mini (PMIN)	PC_{PMIN}	$E_{PC,PMIN}$	-	-	2	Euro 4 - 98/69/EC II	$T_{PC,PMIN,2,E4}$	$PC_{PMIN,E4}$
										Euro 5 - EC 715/2007	$T_{PC,PMIN,2,E5}$	$PC_{PMIN,E5}$
										Euro 6 up to 2016	$T_{PC,PMIN,2,E6-2016}$	$PC_{PMIN,E6-2016}$
										Euro 6 2017 - 2019	$T_{PC,PMIN,2,E6-2019}$	$PC_{PMIN,E6-2019}$
				Petrol Small (PS)	PC_{PS}	$E_{PC,PS}$	-	-	1	PRE ECE	$T_{PC,PS,1,PECE}$	$PC_{PS,PECE}$
										ECE 15/00-01	$T_{PC,PS,1,ECE1}$	$PC_{PS,ECE1}$
										ECE 15/02	$T_{PC,PS,1,ECE2}$	$PC_{PS,ECE2}$
										ECE 15/03	$T_{PC,PS,1,ECE3}$	$PC_{PS,ECE3}$
										ECE 15/04	$T_{PC,PS,1,ECE4}$	$PC_{PS,ECE4}$
										Open Loop (Pre-EEC / Cold Start)	$T_{PC,PS,1,OL}$	$PC_{PS,OL}$

VEHICLE TYPE *(v)*	VEHICLE TYPE % *(V_v)*	FUEL TYPE *(f)*	FUEL TYPE % *($F_{v,f}$)*	VEHICLE SUB-TYPE (ENGINE CAPACITY CATEGORY OR UNLADEN WEIGHT CATEGORY) *(s)*	VEHICLE SUB-TYPE % *(v_s)*	ENGINE CAPACITY % *($E_{v,s}$)*	UNLADEN WEIGHT % *($U_{v,s}$)*	WEIGHTING FACTOR % *(W_v)*	GROUP NUMBER *(n)*	EURO CLASSIFICATION *(e)*	VEHICLE SUB-TYPE BREAKDOWN BY EURO CLASS % *($T_{v,s,n,e}$)*	EURO CLASS % *($v_{s,e}$)*
										Euro 1 - 91/441/EEC	$T_{PC,PS,1,E1}$	$PC_{PS,E1}$
										Euro 2 - 94/12/EEC	$T_{PC,PS,1,E2}$	$PC_{PS,E2}$
										Euro 3 - 98/69/EC I	$T_{PC,PS,1,E3}$	$PC_{PS,E3}$
										Euro 4 - 98/69/EC II	$T_{PC,PS,1,E4}$	$PC_{PS,E4}$
										Euro 5 - EC 715/2007	$T_{PC,PS,1,E5}$	$PC_{PS,E5}$
										Euro 6 up to 2016	$T_{PC,PS,1,E6-2016}$	$PC_{PS,E6-2016}$
										Euro 6 2017 - 2019	$T_{PC,PS,1,E6-2019}$	$PC_{PS,E6-2019}$
										PRE ECE	$T_{PC,PMED,1,PECE}$	$PC_{PMED,PECE}$
										ECE 15/00-01	$T_{PC,PMED,1,ECE1}$	$PC_{PMED,ECE1}$
				Petrol Medium (PMED)	PC_{PMED}	$E_{PC,PMED}$	-	-	1	ECE 15/02	$T_{PC,PMED,1,ECE2}$	$PC_{PMED,ECE2}$
										ECE 15/03	$T_{PC,PMED,1,ECE3}$	$PC_{PMED,ECE3}$
										ECE 15/04	$T_{PC,PMED,1,ECE4}$	$PC_{PMED,ECE4}$

VEHICLE TYPE (*v*)	VEHICLE TYPE % (V_v)	FUEL TYPE (*f*)	FUEL TYPE % ($F_{v,f}$)	VEHICLE SUB-TYPE (ENGINE CAPACITY CATEGORY OR UNLADEN WEIGHT CATEGORY) (*s*)	VEHICLE SUB-TYPE % (v_s)	ENGINE CAPACITY % ($E_{v,s}$)	UNLADEN WEIGHT % ($U_{v,s}$)	WEIGHTING FACTOR % (W_v)	GROUP NUMBER (*n*)	EURO CLASSIFICATION (*e*)	VEHICLE SUB-TYPE BREAKDOWN BY EURO CLASS % ($T_{v,s,n,e}$)	EURO CLASS % ($v_{s,e}$)
										Open Loop (Pre-EEC / Cold-Start)	$T_{PC,PMED,1,OL}$	$PC_{PMED,OL}$
										Euro 1 - 91/441/EEC	$T_{PC,PMED,1,E1}$	$PC_{PMED,E1}$
										Euro 2 - 94/12/EEC	$T_{PC,PMED,1,E2}$	$PC_{PMED,E2}$
										Euro 3 - 98/69/EC I	$T_{PC,PMED,1,E3}$	$PC_{PMED,E3}$
										Euro 4 - 98/69/EC II	$T_{PC,PMED,1,E4}$	$PC_{PMED,E4}$
										Euro 5 - EC 715/2007	$T_{PC,PMED,1,E5}$	$PC_{PMED,E5}$
										Euro 6 up to 2016	$T_{PC,PMED,1,E6-2016}$	$PC_{PMED,E6-2016}$
										Euro 6 2017 - 2019	$T_{PC,PMED,1,E6-2019}$	$PC_{PMED,E6-2019}$
				Petrol Large (PL)	PC_{PL}	$E_{PC,PL}$	-	-	1	PRE ECE	$T_{PC,PL,1,PECE}$	$PC_{PL,PECE}$
										ECE 15/00-01	$T_{PC,PL,1,ECE1}$	$PC_{PL,ECE1}$
										ECE 15/02	$T_{PC,PL,1,ECE2}$	$PC_{PL,ECE2}$

VEHICLE TYPE *(v)*	VEHICLE TYPE % *(V_v)*	FUEL TYPE *(f)*	FUEL TYPE % *($F_{v,f}$)*	VEHICLE SUB-TYPE (ENGINE CAPACITY CATEGORY OR UNLADEN WEIGHT CATEGORY) *(s)*	VEHICLE SUB-TYPE % *(v_s)*	ENGINE CAPACITY % *($E_{v,s}$)*	UNLADEN WEIGHT % *($U_{v,s}$)*	WEIGHTING FACTOR % *(W_v)*	GROUP NUMBER *(n)*	EURO CLASSIFICATION *(e)*	VEHICLE SUB-TYPE BREAKDOWN BY EURO CLASS % *($T_{v,s,n,e}$)*	EURO CLASS % *($v_{s,e}$)*
										ECE 15/03	$T_{PC,PL,1,ECE3}$	$PC_{PL,ECE3}$
										ECE 15/04	$T_{PC,PL,1,ECE4}$	$PC_{PL,ECE4}$
										Euro 1 - 91/441/EEC	$T_{PC,PL,1,E1}$	$PC_{PL,E1}$
										Euro 2 - 94/12/EEC	$T_{PC,PL,1,E2}$	$PC_{PL,E2}$
										Euro 3 - 98/69/EC I	$T_{PC,PL,1,E3}$	$PC_{PL,E3}$
										Euro 4 - 98/69/EC II	$T_{PC,PL,1,E4}$	$PC_{PL,E4}$
										Euro 5 - EC 715/2007	$T_{PC,PL,1,E5}$	$PC_{PL,E5}$
										Euro 6 up to 2016	$T_{PC,PL,1,E6-2016}$	$PC_{PL,E6-2016}$
										Euro 6 2017 - 2019	$T_{PC,PL,1,E6-2019}$	$PC_{PL,E6-2019}$
		Diesel (D)	$F_{PC,D}$	Diesel Small (DS)	PC_{DS}	$E_{PC,DS}$	-	-	2	Euro 4 - 98/69/EC II	$T_{PC,DS,2,E4}$	$PC_{DS,E4}$
										Euro 5 - EC 715/2007	$T_{PC,DS,2,E5}$	$PC_{DS,E5}$
										Euro 6 up to 2016	$T_{PC,DS,2,E6-2016}$	$PC_{DS,E6-2016}$

VEHICLE TYPE *(v)*	VEHICLE TYPE % (V_v)	FUEL TYPE *(f)*	FUEL TYPE % $(F_{v,f})$	VEHICLE SUB-TYPE (ENGINE CAPACITY CATEGORY OR UNLADEN WEIGHT CATEGORY) *(s)*	VEHICLE SUB-TYPE % (v_s)	ENGINE CAPACITY % $(E_{v,s})$	UNLADEN WEIGHT % $(U_{v,s})$	WEIGHTING FACTOR % (W_v)	GROUP NUMBER *(n)*	EURO CLASSIFICATION *(e)*	VEHICLE SUB-TYPE BREAKDOWN BY EURO CLASS % $(T_{v,s,n,e})$	EURO CLASS % $(v_{s,e})$
										Euro 6 2017 - 2019	$T_{PC,DS,2,E6\text{-}2019}$	$PC_{DS,E6\text{-}2019}$
				Diesel Medium (DM)	PC_{DM}	$E_{PC,DM}$	-	-	1	Conventional	$T_{PC,DM,1,CN}$	$PC_{DM,CN}$
										Euro 1 - 91/441/EEC	$T_{PC,DM,1,E1}$	$PC_{DM,E1}$
										Euro 2 - 94/12/EEC	$T_{PC,DM,1,E2}$	$PC_{DM,E2}$
										Euro 3 - 98/69/EC I	$T_{PC,DM,1,E3}$	$PC_{DM,E3}$
										Euro 4 - 98/69/EC II	$T_{PC,DM,1,E4}$	$PC_{DM,E4}$
										Euro 5 - EC 715/2007	$T_{PC,DM,1,E5}$	$PC_{DM,E5}$
										Euro 6 up to 2016	$T_{PC,DM,1,E6\text{-}2016}$	$PC_{DM,E6\text{-}2016}$
										Euro 6 2017 – 2019	$T_{PC,DM,1,E6\text{-}2019}$	$PC_{DM,E6\text{-}2019}$
				Diesel Large (DL)	PC_{DL}	$E_{PC,DL}$	-	-	1	Conventional	$T_{PC,DL,1,CN}$	$PC_{DL,CN}$
										Euro 1 - 91/441/EEC	$T_{PC,DL,1,E1}$	$PC_{DL,E1}$
										Euro 2 - 94/12/EEC	$T_{PC,DL,1,E2}$	$PC_{DL,E2}$

VEHICLE TYPE *(v)*	VEHICLE TYPE % *(V_v)*	FUEL TYPE *(f)*	FUEL TYPE % *($F_{v,f}$)*	VEHICLE SUB-TYPE (ENGINE CAPACITY CATEGORY OR UNLADEN WEIGHT CATEGORY) *(s)*	VEHICLE SUB-TYPE % *(v_s)*	ENGINE CAPACITY % *($E_{v,s}$)*	UNLADEN WEIGHT % *($U_{v,s}$)*	WEIGHTING FACTOR % *(W_v)*	GROUP NUMBER *(n)*	EURO CLASSIFICATION *(e)*	VEHICLE SUB-TYPE BREAKDOWN BY EURO CLASS % *($T_{v,s,n,e}$)*	EURO CLASS % *($v_{s,e}$)*
										Euro 3 - 98/69/EC I	$T_{PC,DL,1,E3}$	$PC_{DL,E3}$
										Euro 4 - 98/69/EC II	$T_{PC,DL,1,E4}$	$PC_{DL,E4}$
										Euro 5 - EC 715/2007	$T_{PC,DL,1,E5}$	$PC_{DL,E5}$
										Euro 6 up to 2016	$T_{PC,DL,1,E6-2016}$	$PC_{DL,E6-2016}$
										Euro 6 2017 - 2019	$T_{PC,DL,1,E6-2019}$	$PC_{DL,E6-2019}$
		LPG (LPG)	$F_{PC,LPG}$	LPG	PC_{LPG}	-	-	W_{PC}	1	Conventional	$T_{PC,LPG,1,CN}$	$PC_{LPG,CN}$
										Euro 1 - 91/441/EEC	$T_{PC,LPG,1,E1}$	$PC_{LPG,E1}$
										Euro 2 - 94/12/EEC	$T_{PC,LPG,1,E2}$	$PC_{LPG,E2}$
										Euro 3 - 98/69/EC I	$T_{PC,LPG,1,E3}$	$PC_{LPG,E3}$
										Euro 4 - 98/69/EC II	$T_{PC,LPG,1,E4}$	$PC_{LPG,E4}$
										Euro 5 - EC 715/2007	$T_{PC,LPG,1,E5}$	$PC_{LPG,E5}$
										Euro 6 - EC 715/2007	$T_{PC,LPG,1,E6}$	$PC_{LPG,E6}$

VEHICLE TYPE (*v*)	VEHICLE TYPE % (V_v)	FUEL TYPE (*f*)	FUEL TYPE % ($F_{v,f}$)	VEHICLE SUB-TYPE (ENGINE CAPACITY CATEGORY OR UNLADEN WEIGHT CATEGORY) (*s*)	VEHICLE SUB-TYPE % (v_s)	ENGINE CAPACITY % ($E_{v,s}$)	UNLADEN WEIGHT % ($U_{v,s}$)	WEIGHTING FACTOR % (W_v)	GROUP NUMBER (*n*)	EURO CLASSIFICATION (*e*)	VEHICLE SUB-TYPE BREAKDOWN BY EURO CLASS % ($T_{v,s,n,e}$)	EURO CLASS % ($v_{s,e}$)
		Hybrid Petrol (H)	$F_{PC,H}$	Hybrid Petrol Small (HPS)	PC_{HPS}	-	-	-	2	Euro 4 and Later	$T_{PC,HPS,2,E4\&L}$	$PC_{HPS,E4\&L}$
				Hybrid Petrol Medium (HPM)	PC_{HPM}					Euro 4 and Later	$T_{PC,HPM,2,E4\&L}$	$PC_{HPM,E4\&L}$
				Hybrid Petrol Large (HPL)	PC_{HPL}					Euro 4 and Later	$T_{PC,HPL,2,E4\&L}$	$PC_{HPL,E4\&L}$
		E85 (E)	$F_{PC,E}$	Ethanol E85 (E)	PC_E	-	-	-	2	Euro 4	$T_{PC,E,2,E4}$	$PC_{E,E4}$
										Euro 5	$T_{PC,E,2,E5}$	$PC_{E,E5}$
										Euro 6	$T_{PC,E,2,E6}$	$PC_{E,E6}$
		CNG (C)	$F_{PC,C}$	CNG (C)	PC_C	-	-	1 - W_{PC}	2	Euro 4	$T_{PC,C,2,E4}$	$PC_{C,E4}$
										Euro 5	$T_{PC,C,2,E5}$	$PC_{C,E5}$
										Euro 6	$T_{PC,C,2,E6}$	$PC_{C,E6}$

The table above highlights the variables required to calculate the percentage of vehicles in each category. The vehicle sub-type Euro Class breakdown ($T_{v,s,n,e}$) is equal to the Estimated Euro Class breakdown for each vehicle type with only one sub-type group whilst further analysis is required to calculate the vehicle sub-type Euro Class breakdown ($T_{v,s,n,e}$) for vehicle types with 2 sub-type groups and the process is described in Section 3.3.5.1.

3.3.5.1. Vehicle Sub-Type Breakdown

The procedure below was used to determine the Vehicle Sub-Type Breakdown by Euro Class percentages ($T_{v,s,n,e}$) for PCs, HDVs and SPSVs in all of the pre-set years within the model, as well as the original model study period. The example below is the calculation of the $T_{v,s,n,e}$ breakdown for passenger cars in 2018. The Irish Bulletin of Vehicle and Driver Statistics 2018 (Department of Transport, Tourism and Sport, 2019) provided statistics on the first year of registration of passenger cars in Ireland, as shown in Table 3.9. Based on these statistics, and the use of the Motorstats database (Motorstats, 2020) for years where Euro Standards were applied within a certain month, an Estimated Euro Class breakdown for 2018 was calculated, as shown in Table 3.10.

Table 3.9: 2018 PCs First Year of Registration (Department of Transport, Tourism and Sport, 2019)

Year First Licensed	No. of Vehicles	Percentage
2018	115 324	5.48%
2017	130 945	6.22%
2016	155 923	7.40%
2015	149 227	7.08%
2014	133 669	6.35%
2013	114 150	5.42%
2012	121 272	5.76%
2011	132 139	6.27%
2010	131 694	6.25%
2009	93 932	4.46%
2008	178 376	8.47%
2007	155 222	7.37%
2006	133 127	6.32%
2005	111 367	5.29%
2004	80 611	3.83%
2003	55 042	2.61%
2002 and Earlier Years	114 349	5.43%
Total	2 106 369	100.00%

Table 3.10: 2018 PCs Estimated Euro Class Breakdown

Euro Class	Percentage
Euro 6 (2017 – 2019)	11.69%
Euro 6 (≤2016)	7.89%
Euro 5	30.39%
Euro 4	32.87%
Euro 3	11.73%
Pre-Euro / Euro 1 / Euro 2 / Euro 3 (2001 – 2002)	5.43%

The next part of the procedure focused on matching the Estimated Euro Class percentages to the Calculated Euro Class percentages which were achieved by multiplying the vehicle type (V_v), fuel type ($F_{v,f}$), sub-type (v_s), engine capacity ($E_{v,s}$), unladen weight ($U_{v,s}$) (for LGVs and HDVs only) and sub-type Euro Class breakdown ($T_{v,s,n,e}$) percentages. Fuel type and engine capacity statistics, shown in Table 3.11 and Table 3.12, were retrieved from the Irish Bulletin of Vehicle and Driver Statistics 2018 (Department of Transport, Tourism and Sport, 2019).

Table 3.11: Fuel Type Breakdown (Department of Transport, Tourism and Sport, 2019)

Fuel Type	No. of Vehicles	Percentage
Petrol	906 528	43.02%
Diesel	1 153 592	54.77%
Petrol & Electric	29 819	1.42%
Diesel & Electric	773	0.04%
Petrol & Ethanol	8 529	0.40%
Electric	4 528	0.21%
Petrol Plug in Hybrid Electric	2 759	0.13%
Diesel Plug in Hybrid Electric	31	0.00%
Other	80	0.00%
Total	2 106 369	100%

Table 3.12: Engine Capacity Breakdown (Department of Transport, Tourism and Sport, 2019)

Engine Capacity (c.c.)	No. of Vehicles	Percentage
Not Exceeding 1 000	152 000	7.22%
1 001 to 1 100	7 495	0.36%
1 101 to 1 200	138 663	6.58%
1 201 to 1 300	119 121	5.66%
1 301 to 1 400	339 348	16.11%
1 401 to 1 500	184 072	8.74%
1 501 to 1 600	447 904	21.26%
1 601 to 1 700	72 730	3.45%
1 701 to 1 800	75 694	3.59%
1 801 to 1 900	76 033	3.61%
1 901 to 2 000	377 052	17.90%
2 001 to 2 100	150	0.01%
2 101 to 2 200	59 319	2.82%
2 201 to 2 300	10 856	0.52%
2 301 to 2 400	2 860	0.14%
2 401 to 2 500	12 432	0.59%
2 501 to 2 600	607	0.03%
2 601 to 2 700	1 013	0.05%
2 701 to 2 800	2 182	0.10%
2 801 to 2 900	113	0.01%
2 901 to 3 000	20 812	0.99%
Exceeding 3 001	5 913	0.28%
Total	2 106 369	100%

The Air Pollutant Emission Inventory Guidebook (European Environment Agency, 2019) categorises engine capacities into 4 sizes (mini, small, medium and large) as shown in Table 3.13. These sizes are only applicable to certain fuel types such as Petrol, Diesel and Hybrid Petrol, and from the engine capacity statistics the breakdowns in Table 3.14 were calculated. The petrol breakdown was directly proportional to the breakdown in Table 3.12 and calculated as shown in Equation 3.22 whilst the Diesel and Hybrid Petrol breakdowns differed slightly in the absence of a mini category and was calculated using the formula in Equation 3.23.

Table 3.13: Fuel Type and Engine Capacity Euro Class Definitions

Fuel / Engine Type	Engine Capacity	Euro Classifications
Petrol Mini	≤1 000 cubic centimetres (c.c.)	Euro 4 and Later
Petrol Small	1 000 – 2 000 c.c.	All Classes
Petrol Medium	2 000 – 3 000 c.c.	All Classes
Petrol Large	≥3 000 c.c.	All Classes
Diesel Small	≤2 000 c.c.	Euro 4 and Later
Diesel Medium	2 000 – 3 000 c.c.	All Classes
Diesel Large	≥3 000 c.c.	All Classes
Liquefied Petroleum Gas	All Capacities	All Classes
Hybrid Petrol Small	≤2 000 c.c.	Euro 4 and Later
Hybrid Petrol Medium	2 000 – 3 000 c.c.	Euro 4 and Later
Hybrid Petrol Large	≥3 000 c.c.	Euro 4 and Later
Ethanol E85	All Capacities	Euro 4 and Later
CNG	All Capacities	Euro 4 and Later

$$Eng.Capacity\ Size\ \% = \sum Eng.Capacity\ \%\ Within\ Size\ Range$$

Eqn. 3.22: Petrol Engine Capacity Size Percentage

$$Eng.Capacity\ Size\ \% = \sum Eng.Capacity\ \%\ Within\ Size\ Range \Big/ \sum Eng.Capacity\ \%\ (Excluding\ Mini\ (< 1\ 000 c.c.)\%)$$

Eqn. 3.23: Diesel and Hybrid Engine Capacity Size Percentage

Table 3.14: Engine Capacity Breakdown by Fuel Type

Fuel Type	Engine Capacity Size	Percentage
Petrol	Mini	7.22%
	Small	87.26%
	Medium	5.24%
	Large	0.28%
Diesel	Small	94.05%
	Medium	5.65%
	Large	0.30%
Hybrid Petrol	Small	94.05%
	Medium	5.65%
	Large	0.30%

Therefore, by multiplying the percentages calculated for each fuel type and engine capacity respectively, the breakdown in PCs shown in Table 3.15 was calculated.

Table 3.15: Full Fuel Type Engine Capacity Breakdown

Fuel Type	Engine Capacity Size	Fuel Type Percentage	Engine Capacity Percentage	Total Percentage
Petrol	Mini	43.02%	7.22%	3.10%
	Small		87.26%	37.55%
	Medium		5.24%	2.25%
	Large		0.28%	0.12%
Diesel	Small	54.77%	94.05%	51.51%
	Medium		5.65%	3.09%
	Large		0.30%	0.17%
LPG	All Sizes	0.00%	100%	0.00%
Hybrid Petrol (Petrol & Electric and Petrol Plug in Hybrid)	Small	1.55%	94.05%	1.45%
	Medium		5.65%	0.09%
	Large		0.30%	0.00%
Ethanol E85	All Sizes	0.40%	100%	0.40%
Electric	All Sizes	0.21%	100%	0.21%
Unaccounted Fuel Type (Diesel & Electric and Diesel Plug in Hybrid)	All Sizes	0.04%	100%	0.04%
Total				100%

As previously stated, vehicle sub-types were separated into two groups based on the Euro Classes within each sub-type. The first group, consisted of sub-types containing all Euro and Pre-Euro Classes and the second group consisted of sub-types containing Euro 4 Class or later. The vehicle sub-types were split into one of these groups and the percentages of PCs within each group calculated, as shown in Table 3.16. The LPG and CNG fuels were categorised as Other in the fuel type statistics of the Irish Bulletin of Vehicle and Driver Statistics and, for this analysis, it was assumed that this category was half LPG and half CNG.

Table 3.16: Fuel Type / Engine Capacity Categories by Euro Class Grouping

Group 1		**Group 2**	
Petrol Small	37.55%	Petrol Mini	3.10%
Petrol Medium	2.25%	Diesel Small	51.51%
Petrol Large	0.12%	Hybrid Petrol Small	1.45%
Diesel Medium	3.09%	Hybrid Petrol Medium	0.09%
Diesel Large	0.17%	Hybrid Petrol Large	0.00%
LPG	0.00% x 50%	Ethanol E85	0.40%
		CNG	0.00% x 50%
Group 1 Total	43.18%	**Group 2 Total**	56.56%

As the exact breakdown by Euro Class for every sub-type was not available, it was assumed that the same breakdown by Euro Class was applicable to all sub-types within a group, as shown in Equation 3.24.

Assumption: $T_{v,s,n,e} = T_{v,s+1,n,e} = T_{v,s+\cdots,n,e} = \cdots$ **Eqn. 3.24: Equal Sub-Type Euro Class Breakdown in Groups**

The equation used to determine the sub-type Euro Class breakdown ($T_{v,s,n,e}$) percentages is shown in Equation 3.25.

$$0.4318\,P_{1,e} + 0.5656\,P_{2,e} = Estimated\ Euro\ Class\ \%$$ **Eqn. 3.25: Sub-Type Euro Class Breakdown Equation**

Where:

$P_{1,e}$ = Percentage of Group 1 Vehicles within a Particular Euro Class

$P_{2,e}$ = Percentage of Group 2 Vehicles within a Particular Euro Class

Using Equations 3.26 and 3.27 and the method of relative proportions between estimated Euro Class percentages, as shown in Table 3.17, the $P_{2,e}$ variable in the equations was calculated. Calculations for this example are shown in Table 3.17 and the subsequent calculations. The $P_{2,e}$ variable within the Euro 4 Class ($P_{2,EURO\ 4}$) was used as the Goal Seek variable (Goal seek is the function within Excel that can change the value within a cell numerous times until another cell (control variable) reaches the required value), as this was the earliest / first Euro Class in Group 2. To calculate the percentages for Euro 3 or earlier classes, the $P_{2,e}$ variable can be removed from Equations 3.26 and 3.27 as Euro 3 is not applicable to the vehicles within Group 2. The control variable for the Goal Seek function was the sum of the $P_{1,e}$ variables which should equal 100%.

$$S_A P_{1,e} + S_{E4\&L} P_{2,e} = EC_{v,y,e}$$ **Eqn. 3.26: Vehicle Sub-Type Euro Class Breakdown Percentage 1**

$$P_{1,e} = {EC_{v,y,e} - S_{E4\&L} P_{2,e}} \Big/ {S_A}$$ **Eqn. 3.27: Vehicle Sub-Type Euro Class Breakdown Percentage 2**

Table 3.17: Method of Relative Proportions

	Euro Class Breakdown	Relative Proportion	$P_{2,e}$ Variable
Euro 6 (2017 - 2019)	11.69%		= (0.24 x 1.48) $P_{2,e}$ = 0.36 $P_{2,e}$
	↑	x 1.48	
Euro 6 (≤2016)	7.89%		= (0.92 x 0.26) $P_{2,e}$ = 0.24 $P_{2,e}$
	↑	x 0.26	
Euro 5	30.39%		= 0.92 $P_{2,e}$
	↑	x 0.92	
Euro 4	32.87%		= $P_{2,e}$ ***(Goal Seek Variable)***
	↑	x 2.80	
Euro 3	11.73%		
	↑	x 2.16	
Pre-Euro / Euro 1 / Euro 2 / Euro 3 (2001 – 2002)	5.43%		

Using Equations 3.26 and 3.27 above and the relative proportions from Table 3.17, formulas in terms of $P_{2,EURO\ 4}$ (the Goal Seek variable) were determined for each of the Euro Classes in Group 1, as shown in Table 3.18.

Table 3.18: Group 1 Euro Class Breakdown Percentage Calculations

Euro Class	Percentage Calculation
Pre-Euro / Euro 1 / Euro 2	$\mathbf{P_{1,PRE\text{-}EURO}}$ = 5.43% / 0.4318
Euro 3	$\mathbf{P_{1,EURO\ 3}}$ = 11.73% / 0.4318
Euro 4	$\mathbf{P_{1,EURO\ 4}}$ = (32.87%-0.5656 x $P_{2,EURO\ 4}$) / 0.4318
Euro 5	$\mathbf{P_{1,EURO\ 5}}$ = (30.39%-0.5656 x 0.92 x $P_{2,EURO\ 4}$) / 0.4318
Euro 6 (≤2016)	$\mathbf{P_{1,EURO\ 6\ (\leq 2016)}}$ = (7.89%-0.5656 x 0.24 x $P_{2,EURO\ 4}$) / 0.4318
Euro (2017 – 2019)	$\mathbf{P_{1,EURO\ 6\ (2017-2019)}}$ = (11.69%-0.5656 x 0.36 x $P_{2,EURO\ 4}$) / 0.4318

Therefore, the vehicle sub-type Euro Class breakdown ($T_{v,s,n,e}$) assigned to the sub-types within Group 1 are shown in Table 3.19.

Table 3.19: Group 1 Euro Class Breakdown Percentages

Euro Class	Percentage
Pre-Euro / Euro 1 / Euro 2	12.57%
Euro 3	27.16%
Euro 4	23.91%
Euro 5	22.11%
Euro 6 (≤2016)	5.74%
Euro 6 (2017 – 2019)	8.51%

A separate calculation was then prepared for the Group 2 breakdown, whereby, only the relative proportions from the Estimated Euro Class percentages were used and the GOAL SEEK function was used on the sum of the $P_{2,e}$ variables which should equal 100% (i.e. all vehicles contained within Group 2). Formulas for the $P_{2,e}$ variables for each of the Euro Classes within Group 2 are shown in Table 3.20.

Table 3.20: Group 2 Euro Class Breakdown Percentage Calculations

Euro Class	Percentage Calculation
Euro 4	$= P_{2,EURO\ 4}$
Euro 5	$\mathbf{P_{2,EURO\ 5}} = 0.92 \times P_{2,EURO\ 4}$
Euro 6 (≤2016)	$\mathbf{P_{2,EURO\ 6\ (\leq 2016)}} = 0.92 \times 0.26 \times P_{2,EURO\ 4}$
Euro 6 (2017 – 2019)	$\mathbf{P_{2,EURO\ 6\ (2017-2019)}} = 0.92 \times 0.26 \times 1.48 \times P_{2,EURO\ 4}$

Therefore, the vehicle sub-type Euro Class breakdown ($T_{v,s,n,e}$) assigned to the sub-types within Group 2 are shown in Table 3.21.

Table 3.21: Group 2 Euro Class Breakdown Percentages

Euro Class	Percentage
Euro 4	39.68%
Euro 5	36.69%
Euro 6 (≤2016)	9.53%
Euro 6 (2017 – 2019)	14.11%

3.3.5.2. Passenger Cars (PCs)

Table 3.22 shows the Estimated Euro Class percentages ($EC_{v,y,e}$) for the original model period as well as for each of the pre-set years included in the amended model. The Calculated Euro Class percentages ($v_{s,e}$) for Passenger Cars used to determine the average emissions from a Passenger Car are also provided. The Estimated and Calculated Breakdowns for each Passenger Car Euro Class were the same for the original study period and only had minimal differences in any of the pre-set years.

A number of significant changes were noticed in the passenger car fleet since the original study period. Approximately 21% of all passenger cars between 2010 and 2012 were Euro 2 or older classification, whilst by the year 2016, this percentage had dropped below 6% and continued to drop through 2018. Similarly, vehicles Euro 3 or older also had reduced considerably from approximately 60% in the original study period to approximately 17% in 2018. This transition from older Euro Classes would result in lower emissions from the fleet as the newer Euro Class vehicles have considerably lower limits across a range of emissions and fuel types, as shown in Table 2.3.

Euro 5 or newer Euro Classes increased by a similar amount over the same time period from approximately 4% during the original study period to approximately 50% in 2018. However, this reduction in older Euro Classes did not directly translate to the newest available Euro Class in any given year as by 2016, the Euro 4 class had increased by approximately 0.4% in comparison to the original study period and the Euro 5 Class, which was 4.4% of the fleet in the original study period, increased year-on-year from approximately 26% in 2016 to 28.3% in 2017 to 30.4% in 2018. The Euro 6 class (≤2016) increased slightly year-on-year from 2016 onwards despite not being the newest Euro Class also. These changes highlighted the increased popularity of the second hand vehicle market in Ireland during this time period, which in turn would slow down the rate of improvement in average emissions within the passenger car fleet.

Table 3.22: Passenger Cars (PCs) Euro Classification Breakdown Calculated Percentages (Estimated Percentages)

Euro Classification		Original Model (2010 – 2012)	2016	2017	2018
Pre-Euro / Euro 1	Calculated %	3.25%	-	-	-
	Estimated %				
Pre-Euro / Euro 1 / Euro 2	Calculated %	-	5.89%	-	-
	Estimated %		*5.88%*		
Pre-Euro / Euro 1 / Euro 2 / Euro 3 (2001)	Calculated %	-	-	5.65%	-
	Estimated %			*5.64%*	
Pre-Euro / Euro 1 / Euro 2 / Euro 3 (2001 – 2002)	Calculated %	-	-	-	5.44%
	Estimated %				*5.43%*
Euro 2	Calculated %	17.73%	-	-	-
	Estimated %				
Euro 3	Calculated %	38.87%	24.85%	17.86%	11.76%
	Estimated %		*24.83%*	*17.83%*	*11.73%*
Euro 4	Calculated %	35.75%	36.18%	34.91%	32.85%
	Estimated %		*36.19%*	*34.93%*	*32.87%*
Euro 5	Calculated %	4.40%	25.95%	28.28%	30.38%
	Estimated %		*25.96%*	*28.29%*	*30.39%*
Euro 6 (≤2016)	Calculated %	0.00%	7.13%	7.48%	7.89%
	Estimated %				
Euro 6 (2017 – 2019)	Calculated %	0.00%	0.00%	5.82%	11.69%
	Estimated %				

3.3.5.3. LCVs

The Estimated ($EC_{v,y,e}$) and Calculated ($v_{s,e}$) Euro Class Breakdowns for LCVs, shown in Table 3.23, were equal for all Euro Classes and every year / period as the complexity of two Vehicle Sub-Type Breakdown by Euro Class ($T_{v,s,n,e}$) groups was not applicable to the LCVs.

From the original study period to 2016, there was a significant uptake in Euro 5 vehicles from approximately 1% between 2010 and 2012 to approximately 24% in 2016. Up until September 2015, Euro 5 was the newest Euro Class for LCVs less than 1305kg unladen weight, and September 2016, for LCVs greater than 1305kg unladen weight, therefore, the largest increase was in this classification from the original study period to 2016. The small percentage of Euro Class 6 in 2016 was mainly due to this new classification only being introduced for the most popular unladen weight range (greater than 1305kg) part way through 2016 (Department of Transport, Tourism and Sport, 2017; Motorstats, 2020).

The transition from older Euro Classes is also evident in the LCVs fleet as the percentage of vehicles in classes up to Euro 4 reduced year on year from 2016 to 2018. These classes accounted for approximately 74% of all vehicles in 2016, 66% in 2017 and 58% in 2018. The largest percentage increase in 2017 and 2018 were in the newest Euro Classification available in the respective years. In 2017, an increase of approximately 6.7% was observed in the Euro 6 (≤2017) Class, whilst the only other increase was in the Euro 5 Class, of approximately 1% which indicates a small influence from the second hand vehicle market. In 2018, a similar increase was observed again in the Euro 5 Class and the Euro 6 (≤2017) Class was relatively the same percentage as 2017 but the new Euro Class (Euro 6 2018 – 2020) accounted for 7% of the LCV fleet, showing a positive trend in changes towards newer and cleaner Euro Classes.

Table 3.23: LCVs Euro Classification Breakdown Calculated Percentages (Estimated Percentages)

Euro Classification		**Original Model (2010 – 2012)**	**2016**	**2017**	**2018**
Pre-Euro / Euro 1	Calculated % / *Estimated %*	7.36%	-	-	-
Pre-Euro / Euro 1 / Euro 2 (≤2000)	Calculated % / *Estimated %*	-	6.98%	-	-
Pre-Euro / Euro 1 / Euro 2 / Euro 3 (2001)	Calculated % / *Estimated %*	-	-	7.75%	-
Pre-Euro / Euro 1 / Euro 2 / Euro 3 (2001 – 2002)	Calculated % / *Estimated %*	-	-	-	8.29%
Euro 2	Calculated % / *Estimated %*	15.07%	2.44%	-	-
Euro 3	Calculated % / *Estimated %*	44.87%	32.56%	27.92%	21.12%
Euro 4	Calculated % / *Estimated %*	31.66%	31.62%	30.22%	28.44%
Euro 5	Calculated % / *Estimated %*	1.03%	24.34%	25.40%	26.38%
Euro 6 (≤2017)	Calculated % / *Estimated %*	0.00%	2.05%	8.71%	8.77%
Euro 6 (2018 – 2020)	Calculated % / *Estimated %*	0.00%	0.00%	0.00%	7.01%

3.3.5.4. HDVs and LPSVs

The Estimated ($EC_{v,y,e}$) and Calculated ($v_{s,e}$) Euro Class Breakdowns for HDVs and LPSVs are shown in Table 3.24. Differences between Estimated and Calculated Breakdowns for HDVs were minimal for every Euro Class in every time period. In the case of LPSVs, it was assumed that the Estimated Euro Class Breakdown for LPSVs was the same as HDVs, due to the absence of data for the first year of registration of LPSVs. This assumption was mainly based on the fact that the HDVs and LPSVs are covered by the same Euro Classification system (Euro I, Euro II, Euro III, etc.) as well as the fact that the average emissions from HDVs and LPSVs were similar for both vehicle types (European Environment Agency 2019). The Estimated ($EC_{v,y,e}$) and Calculated ($v_{s,e}$) Euro Class Breakdowns for LPSVs were equal as shown in Table 3.24.

The Euro Class breakdown for HDVs and LPSVs showed a positive transition to the newest available Euro Class year on year from 2016 to 2018, with only the Euro VI Class increasing by approximately 8% in 2017 and another 8% in 2018. A significant difference regarding the Euro Classes was noted for the HDVs and LPSVs fleet in comparison to the passenger cars and LCVs. The newest Euro Class (Euro VI) was introduced in 2013 and the next class (Euro V) was introduced in 2008. By 2018, these classes would represent all vehicles which were within 10 years of their first year of registration. Therefore, the transition towards newer Euro Classes since the original period, mainly to Euro VI, and the high percentage of newer vehicles within the HDVs and LPSVs fleet (54% in 2017 and 61% in 2018) was expected due to the length of time since an update in the Euro Classification for these vehicle types.

Table 3.24: HDVs and LPSVs Euro Classification Breakdown Calculated Percentages (Estimated Percentages)

Euro Classification		**Original Model (2010 – 2012)**	**2016**	**2017**	**2018**
Pre-Euro / Euro I	HDVs Calculated %	4.33%	-	-	-
	LPSVs Calculated %	4.35%			
	Estimated %	*4.35%*			
Pre-Euro / Euro I / Euro II / Euro III (2000)	HDVs Calculated %	-	6.94%	-	-
	LPSVs Calculated %		6.98%		
	Estimated %		*6.98%*		
Pre-Euro / Euro I / Euro II / Euro III (2000 – 2001)	HDVs Calculated %	-	-	7.71%	-
	LPSVs Calculated %			7.75%	
	Estimated %			*7.75%*	
Pre-Euro / Euro I / Euro II / Euro III (2000 – 2002)	HDVs Calculated %	-	-	-	8.22%
	LPSVs Calculated %				8.29%
	Estimated %				*8.29%*
Euro II	HDVs Calculated %	8.16%	-	-	-
	LPSVs Calculated %	8.16%			
	Estimated %	*8.16%*			
Euro III	HDVs Calculated %	34.37%	17.84%	12.50%	7.61%
	LPSVs Calculated %	34.37%	17.83%	12.49%	7.60%
	Estimated %	*34.37%*	*17.83%*	*12.49%*	*7.60%*
Euro IV	HDVs Calculated %	35.34%	29.11%	26.11%	23.04%
	LPSVs Calculated %	35.33%	29.09%	26.10%	23.02%
	Estimated %	*35.33%*	*29.09%*	*26.10%*	*23.02%*
Euro V	HDVs Calculated %	17.79%	22.02%	21.87%	21.17%
	LPSVs Calculated %	17.79%	22.01%	21.86%	21.15%
	Estimated %	*17.79%*	*22.01%*	*21.86%*	*21.15%*
Euro VI	HDVs Calculated %	0.00%	24.10%	31.82%	39.97%
	LPSVs Calculated %		24.09%	31.81%	39.94%
	Estimated %		*24.09%*	*31.81%*	*39.94%*

3.3.5.5. Motorcycles

Data for the first year of registration of the motorcycle fleet was not available for any of the pre-set years or original study period. Therefore an Estimated Euro Class Breakdown was generated as described here. It was assumed that the first year of registration breakdown for motorcycles was equal to the average first year of registration breakdown of PCs and LCVs combined. Motorcycles are mainly private owned vehicles, as is the case for PCs and LCVs, and so it was expected that trends in the upgrading of the motorcycle fleet (change from older to newer Euro Class vehicles) would be similar to that for PCs and LCVs. The Estimated Euro Class Breakdown ($EC_{v,y,e}$) was equal to the Calculated Euro Class Breakdown ($v_{s,e}$) for motorcycles for all years / periods, as shown in Table 3.25.

Similar to the HGVs and LPSVs, a significant period of time had passed for an update in the Euro Classification of motorcycles, with Euro 3 introduced for the first time in July 2007 and only superseded in 2016. The Emissions Inventory Guidebook (European Environment Agency, 2019) which was used to gauge the average emissions from each vehicle type and Euro Class, grouped all motorcycles Euro 3 or newer into one group and the statistics below reflect this collation of all motorcycles Euro 3 and newer. Therefore, it was expected that by 2016 and onwards that the most common Euro Class in the fleet was Euro 3. Between 2016 and 2018, a significant transition from older Euro Classes was noticed, as the Pre-Euro / Euro 1 Class reduced by approximately 12% and the Euro 2 Class reduced by approximately 4%.

Table 3.25: Motorcycles Euro Classification Breakdown Calculated Percentages (Estimated Percentages)

Euro Classification		Original Model (2010 – 2012)	2016	2017	2018
Pre-Euro	Moped Calculated % / *Moped Estimated %*	0.87%	-	-	-
	Motorcycles <250 c.c. Calculated % / *Motorcycles <250 c.c. Estimated %*	2.33%			
	Motorcycles >250 c.c. Calculated % / *Motorcycles >250 c.c. Estimated %*	9.11%			
Pre-Euro / Euro 1	Moped Calculated % / *Moped Estimated %*	-	0.65%	0.41%	0.29%
	Motorcycles <250 c.c. Calculated % / *Motorcycles <250 c.c. Estimated %*		4.49%	3.46%	2.46%
	Motorcycles >250 c.c. Calculated % / *Motorcycles >250 c.c. Estimated %*		23.60%	18.27%	13.61%
Euro 1	Moped Calculated % / *Moped Estimated %*	1.46%	-	-	-
	Motorcycles <250 c.c. Calculated % / *Motorcycles <250 c.c. Estimated %*	8.62%			
	Motorcycles >250 c.c. Calculated % / *Motorcycles >250 c.c. Estimated %*	33.69%			
Euro 2	Moped Calculated % / *Moped Estimated %*	3.13%	1.90%	1.52%	1.22%
	Motorcycles <250 c.c. Calculated % / *Motorcycles <250 c.c. Estimated %*	3.72%	2.56%	2.34%	2.00%
	Motorcycles >250 c.c. Calculated % / *Motorcycles >250 c.c. Estimated %*	14.53%	13.46%	12.39%	11.06%
Euro 3	Moped Calculated % / *Moped Estimated %*	1.59%	2.92%	3.10%	3.42%
	Motorcycles <250 c.c. Calculated % / *Motorcycles <250 c.c. Estimated %*	4.27%	8.06%	9.31%	10.09%
	Motorcycles >250 c.c. Calculated % / *Motorcycles >250 c.c. Estimated %*	16.69%	42.36%	49.21%	55.85%

3.3.5.6. Small Public Service Vehicles (SPSVs)

There was no data available for the Small Public Service Vehicles (SPSVs) and therefore no Estimated Euro Class Breakdown ($EC_{v,y,e}$) could be calculated. The assumptions used for the motorcycles could not be used for the SPSVs as a number of restrictions were applicable to this vehicle type. Vehicles within the SPSV category must not be older than 10 years from the date of first registration if they are standard taxis. For taxis modified for wheelchair use or vehicles with taxi licenses which were permitted before 1st January 2009 and still active on the 1st January 2013 the limit is 15 years from the date of first registration of the vehicle (National Transport Authority, 2015). The Commission for Taxi Regulation (Commission for Taxi Regulation, 2007) identified specific models of vehicles (Toyota Avensis, Skoda Octavia, Nissan Primera and Volkswagen Passat) which meet all the requirements of a taxi. Upon analysing these vehicle models, it was determined that none of these vehicles had engine capacities less than 1 000 c.c. Therefore, the petrol mini category was excluded from the SPSVs Euro Class breakdown. The Vehicle Sub-Type Euro Class Breakdowns ($T_{v,s,n,e}$) assigned to the SPSVs were the same as those used for the PCs, except in the case where vehicles are older than 15 years from date of first registration. If this was the case, this percentage would be included in the oldest Euro Class which is considered acceptable for the SPSVs in accordance with the National Vehicle Standards – Requirements for Small Public Service Vehicles (Commission for Taxi Regulation, 2007). The Calculated Euro Class Breakdowns for each time period are shown in Table 3.26.

The breakdown below shows that by the year 2016, there were no Euro 1 or Euro 2 Class vehicles within the SPSVs fleet and this would have been the case due to the restrictions in the National Vehicle Standards. The Euro 3 and Euro 4 percentages reduced by approximately 5% and 10% respectively between 2016 and 2018; and these reductions could have been influenced by the approaching expiration of the vehicle under the National Vehicle Standards - Requirements from Small Public Service Vehicles. The Euro 6 (≤2016) was largely unchanged between 2016 and 2018, whilst Euro 5 increased by approximately 1% and Euro 6 (2017 – 2019) showed significant increases since it was introduced. This shows a positive transition to newer Euro Classes with a small influence from the second hand vehicle market contributing to the minor increase in Euro 5 percentages.

Table 3.26: SPSVs Euro Classification Breakdown Calculated Percentages

Euro Classification	Original Model (2010 – 2012)	2016	2017	2018
Euro 1	1.33%	0.00%	0.00%	0.00%
Euro 2	7.25%	0.00%	0.00%	0.00%
Euro 3	15.89%	7.23%	4.58%	2.61%
Euro 4	67.26%	48.47%	43.55%	38.65%
Euro 5	8.28%	34.76%	35.28%	35.71%
Euro 6 (≤2016)	0.00%	9.55%	9.33%	9.28%
Euro 6 (2017 – 2019)	0.00%	0.00%	7.26%	13.74%

3.4. Conclusion

This chapter presented the WS-LUR equation for the Original Model Methodology developed by Naughton et al. (2018) and the proposed changes to the equation which focused on differentiating flows for vehicle types within the IDWVKT variable. This was achieved by applying a weighting on each vehicle type based on their average emission rate compared to the average emission rate of a unit vehicle within the national vehicle fleet.

The methodology and data sources for the analysis of each of the variables within the WS-LUR model were introduced. The statistics produced from this analysis would form the background data within the WS-LUR model, described in more detail in Chapter 4, which could be used by the modeller to determine NO_2 concentrations at any location within the East Region (Leinster and Monaghan) during one of the pre-set year options (2016 to 2018) without having to collect any further data. These pre-set options within the WS-LUR model were used to re-validate the Original Model Methodology and validate the New Model Methodologies, the results of which are presented in Chapter 5.

The Calculated Euro Class Breakdowns for each vehicle type (Sections 3.3.5.2, 3.3.5.3, 3.3.5.4, 3.3.5.5 and 3.3.5.6) were utilised in combination with the average emissions for every vehicle type from the Air Pollutant Emission Inventory Guidebook (European Environment Agency, 2019) to determine the average emission from a vehicle in each of the pre-set years and the original model. The results of this element of the analysis are provided in Section 5.1.1.

4. Model Features

In this chapter, the structure of the WS-LUR model is described as well as the step-by-step process of using the enhanced model to determine the ambient NO_2 concentration for any location during one of three pre-set years or using a manual entry approach. A number of functions were included in the model to reduce errors and to simplify the input process for the modeller and these are explained in detail in this chapter also.

The enhanced WS-LUR model for calculating ambient NO_2 concentrations was developed in Microsoft Excel. A number of data analytics software programs (R Programming, Tableau Public, SAS, Apache Spark, etc.) were considered for the development of the model. Excel was selected

1. to maximise accessibility to the model, with a view to future use and development;
2. to minimise the training required to utilise the basic functions of the model - the model has been designed so that all functions or commands are programmed in the background and key spreadsheets automatically update when the modeller inputs a value;
3. to facilitate data management - data for this research are obtained from a number of different sources that are typically available in an Excel compatible format or can be transferred to Excel format after the main elements of the analysis have been completed.

The model has two modes of operation. The first is an automatic calculation where the modeller selects from one of the pre-set years included in the model, (2016 to 2018), and the model calculates NO_2 concentrations using the data saved in the background. The other mode is the manual entry method in which the modeller enters the required data for a specific location and the resultant concentration is calculated. This mode supports the calculation of future or past concentrations.

The model contains a section which summarises variable values (meteorological, land use, commercial properties, IDWVKT and road density) in each wind direction sector as well as the concentration contribution from each wind direction sector. Other sections within the model allow the modeller to analyse concentrations in future or past time periods and also to analyse potential mitigation measures by altering the values of the meteorological, land use, commercial properties, IDWVKT and road density variables within the model. The step-by-step process to calculate the NO_2 concentration at a location is shown in Figure 4.1 and described in detail in Section 4.1.

STEP 1: SELECTION OF STUDY PERIOD/ ANALYSIS METHOD

Input data for a number of Pre-Set Years (2016, 2017, 2018) are stored within the model, which can automatically calculate annual concentrations for these years for any location nationwide. Manual Entry Analysis is an alternative option where the modeller can enter data for each variable and calculate the concentration for a specific location and time.

STEP 2: SELECTION OF LOCATION

When one of the Pre-Set Years are selected the modeller must provide the co-ordinates of the study location. This option is not compulsory for Manual Entry Analysis but is useful for future reference to identify the study location. For Manual Entry Analysis skip to Step 4.

STEP 3: SELECTION OF TRIANGULATION ACCURACY

The triangulation accuracy must be specified when one of the Pre-Set Years are selected. This step is necessary to determine the number of meteorological stations that are used to interpolate meteorological variables at the study location. For Pre-Set Year Analysis, skip to Step 5.

STEP 4: DATA INPUT

For Manual Entry Analysis, the meteorological, land use, commercial properties and traffic data are entered in the assigned sections of the model.

STEP 5: SELECTION OF INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED CALCULATION METHOD

A number of analysis types are available for selection in the model which can change the method used to calculate the Inverse Distance Weighted Vehicle Kilometres Travelled variable. The various analysis types are explored in Section 4.1.

STEP 6: CALCULATION OF NO_2 CONCENTRATIONS

Once all the above steps are completed in the model, the NO_2 concentration at the specified location is calculated using the WS-LUR equation and a summary of the total NO_2 concentration and the contributions from each wind direction sector are output.

Figure 4.1: Model Input Step-by-Step Process

4.1. Model Spreadsheets / Sections

This section describes the purpose and structure of the various Excel spreadsheets in the WS-LUR model, which includes an input sheet and a number of manual entry data sheets for each of the variables in the model (meteorological, natural/agricultural land use, commercial properties, road density and IDWVKT).

4.1.1. Input Sheet

The Input Sheet is the main step in calculating the NO_2 concentration for a specific location. In the General Details section, the modeller confirms the analysis type they wish to use in the model: either one of the pre-set years or manual entry analysis, as described in Chapter 3. If one of the pre-set years is selected, the modeller must then specify the study location co-ordinates using TM65 Irish Grid system format. Since the analysis was carried out on a 50 x 50m grid spacing for a number of the dependent variables, all co-ordinates entered in the model should be multiples of 50 in order for calculations to be carried out accurately. If not, the results will represent a mix of data from the specified point and the nearest 50 x 50 co-ordinate sample point. If the co-ordinates entered by the modeller match the co-ordinates of a monitoring station from which data was taken, the modeller is notified of this, as shown in Figure 4.2. The triangulation accuracy is also specified at this stage, which allows the modeller to set the number of points included in the meteorological data interpolation calculation. Figure 4.3 shows the layout of the General Details section of the Input Sheet, including the additional notes which have been added to assist the modeller when completing this section. All summary sheets described in Section 3.3 are linked to the values input by the modeller in this section.

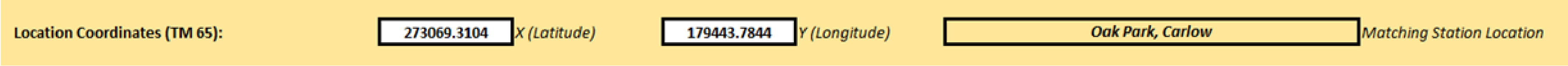


Figure 4.2: Matching Monitoring Station Location Notification

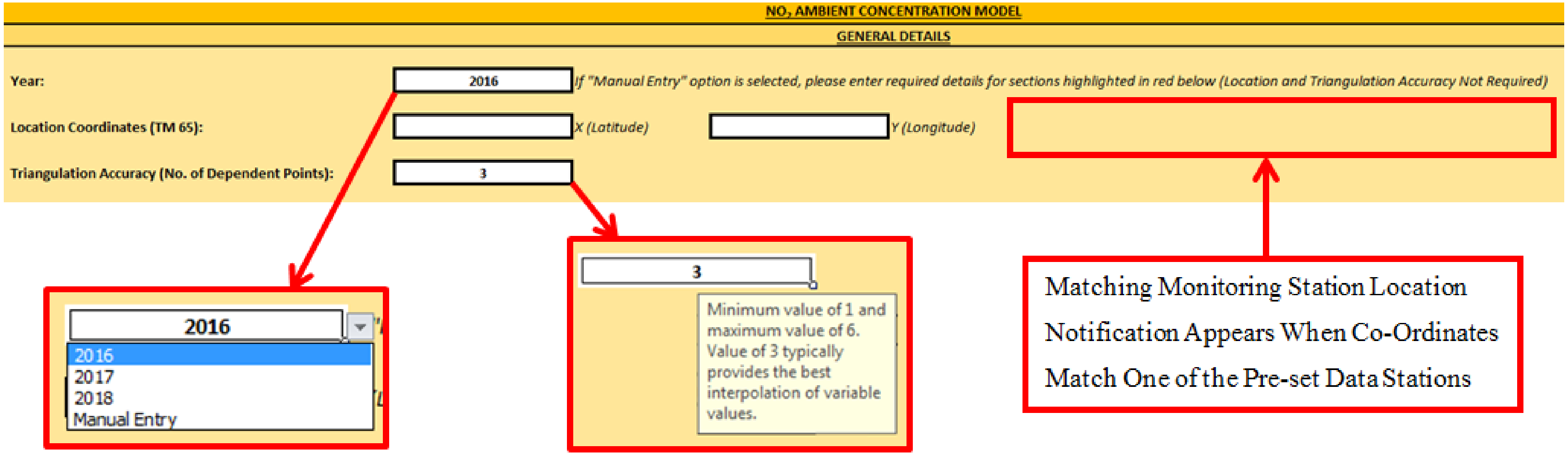


Figure 4.3: Input Sheet - General Details Section

The next sections of the Input Sheet are summaries of the meteorological, land use, commercial properties and traffic variables, as shown in Figure 4.4. If one of the pre-set years was selected in the General Details section, the modeller just needs to specify the method to be used to calculate the Inverse Distance Weighted Vehicle Kilometres Travelled (IDWVKT) variable in the Traffic Details section. The 3 options available within a dropdown list are:

- **Original Model – AADT Only:** This option will calculate the IDWVKT values as per the original model methodology by Naughton et al. (2018) in which only the AADT value is considered and all vehicle types are weighted equally.
- **New Model A – Original Vehicle Type Composition:** This option will calculate the IDWVKT values using the vehicle type breakdown and NO_2 emission weightings calculated for the 2010 to 2012 study period, as described in Section 3.2.
- **New Model B – Vehicle Type and Euro Classification:** This option will calculate the IDWVKT values using the vehicle type breakdown and NO_2 emission weightings calculated for the pre-set year selected in the General Details section, as described in Section 3.2.

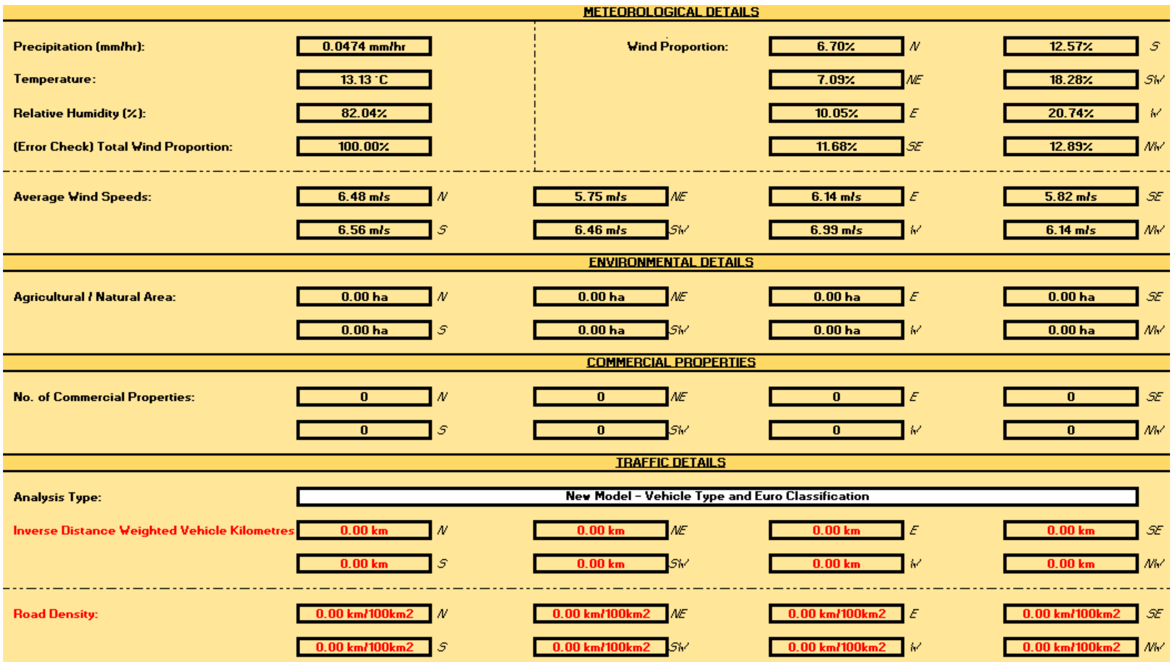
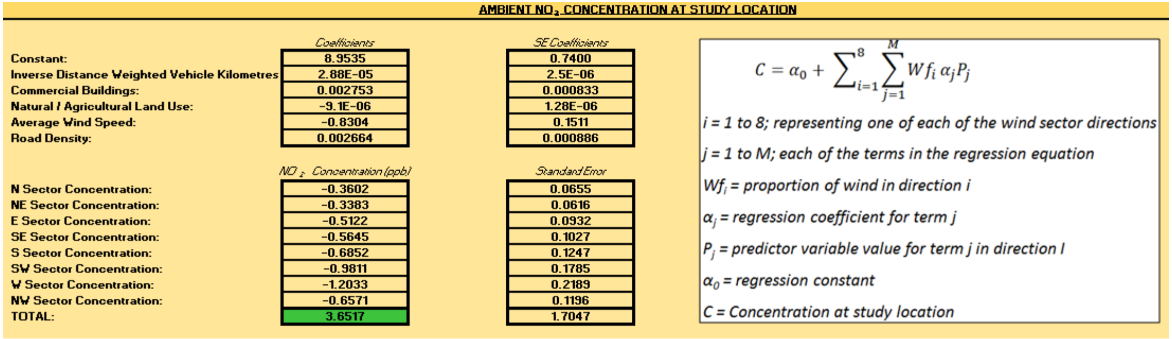


Figure 4.4: Input Sheet - Dependent Variables Summaries

The final section of the Input Sheet is where the regression coefficients are applied to the variable values and the ambient NO_2 concentration of the study location is calculated, as shown in Figure 4.5. The breakdown of the concentration attributable to each wind sector and the standard error of these values are also provided, which assists in identifying the locations of the most significant pollutant sources.



AMBIENT NO_2 CONCENTRATION AT STUDY LOCATION

	Coefficients	SE Coefficients
Constant:	8.9535	0.7400
Inverse Distance Weighted Vehicle Kilometres	2.88E-05	2.5E-06
Commercial Buildings:	0.002753	0.000833
Natural / Agricultural Land Use:	-9.1E-06	1.28E-06
Average Wind Speed:	-0.8304	0.1511
Road Density:	0.002664	0.000886

	NO_2 Concentration (ppb)	Standard Error
N Sector Concentration:	-0.3602	0.0655
NE Sector Concentration:	-0.3383	0.0616
E Sector Concentration:	-0.5122	0.0932
SE Sector Concentration:	-0.5645	0.1027
S Sector Concentration:	-0.6852	0.1247
SW Sector Concentration:	-0.9811	0.1785
W Sector Concentration:	-1.2033	0.2189
NW Sector Concentration:	-0.6571	0.1196
TOTAL:	3.6517	1.7047

$$C = \alpha_0 + \sum_{i=1}^{8} \sum_{j=1}^{M} Wf_i \, \alpha_j P_j$$

i = 1 to 8; representing one of each of the wind sector directions

j = 1 to M; each of the terms in the regression equation

Wf_i = proportion of wind in direction *i*

α_j = regression coefficient for term *j*

P_j = predictor variable value for term *j* in direction *I*

α_0 = regression constant

C = Concentration at study location

Figure 4.5: Input Sheet - Ambient NO_2 Concentration at Study Location Section

4.1.2. Section A (Manual Meteorological Data Entry)

Section A of the model is only applicable when the manual entry option is selected in the General Details section of the Input Sheet. In this section the modeller can add custom meteorological data such as precipitation, temperature, relative humidity, wind speed and direction. The required units for each variable are provided at the top of the manual entry columns, and in a number of cases, the modeller can select from a number of units, as shown in Figure 4.6. Irrespective of which unit is selected in the manual entry section, the values that are transferred to the data summary section in the Input Sheet are converted to the compatible units. Sufficient empty cells are provided for a year of hourly data (8 784 rows) for each variable, but data for a shorter time period can also be analysed.

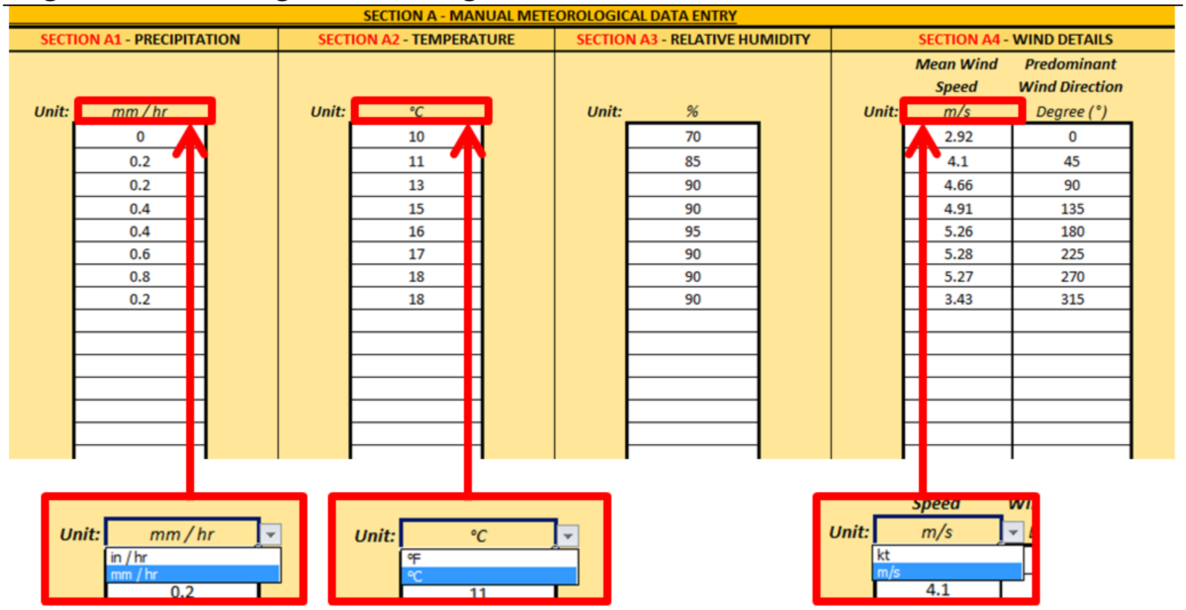


Figure 4.6: Section A - Manual Meteorological Data Entry

In certain cases, the modeller may already have an average wind speed for each sector but if these values were included in the model as eight separate values, it would automatically assume the proportion was equal for each sector (12.5%). Therefore, Section A5 has been included in the model to allow the modeller to overwrite this assumption and manually assign proportions, as shown in Figure 4.7.

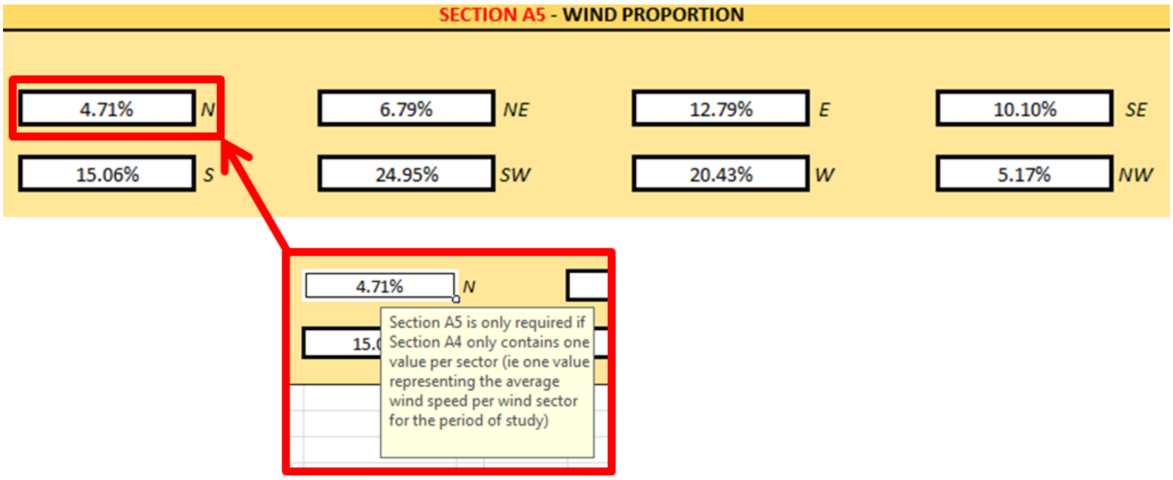
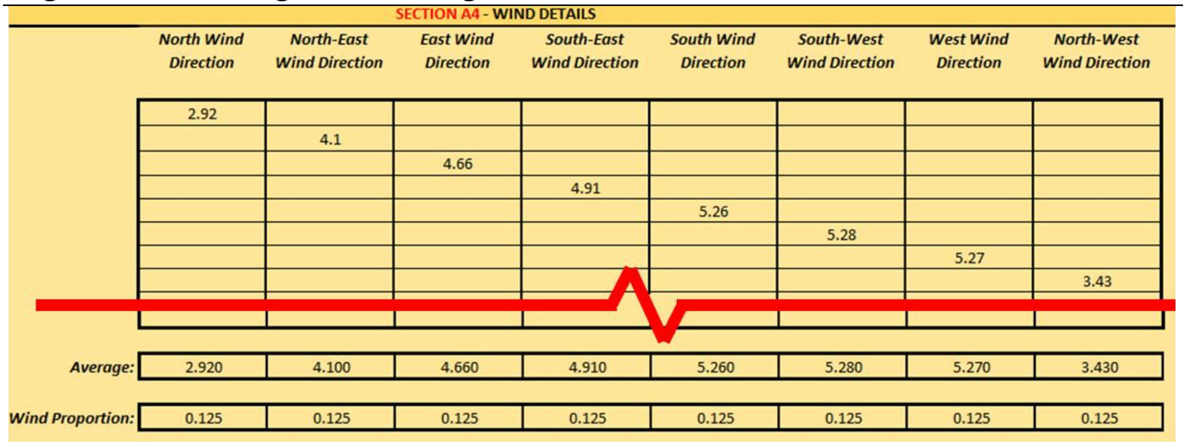


Figure 4.7: Section A - Manual Wind Direction Proportions

All values entered by the modeller are then consolidated into a separate table by assigning the values to one of eight columns representing each of the wind sector directions, as shown in Figure 4.8.



SECTION A4 - WIND DETAILS

	North Wind Direction	North-East Wind Direction	East Wind Direction	South-East Wind Direction	South Wind Direction	South-West Wind Direction	West Wind Direction	North-West Wind Direction
	2.92							
		4.1						
			4.66					
				4.91				
					5.26			
						5.28		
							5.27	
								3.43
Average:	2.920	4.100	4.660	4.910	5.260	5.280	5.270	3.430
Wind Proportion:	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125

Figure 4.8: Section A - Manual Meteorological Data Calculation Table

4.1.3. Section B (Manual Agricultural/Natural Land Use Data Entry)

Section B is the second of four sections required for the manual entry procedure and this is the section where custom data for the agricultural / natural area is entered. Values can be entered in hectares (ha) or square metres (m^2) in each of the sector direction cells as shown in Figure 4.9, and are then converted to the correct units for the results displayed on the Input Sheet.

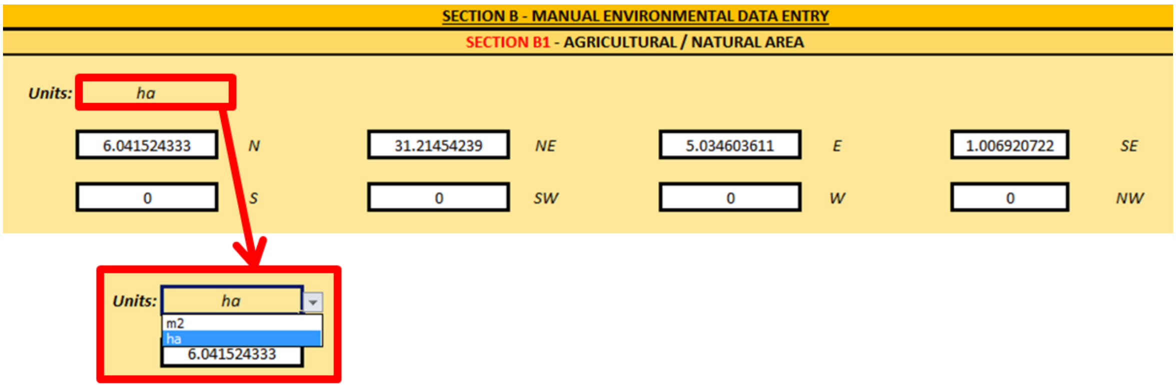


Figure 4.9: Section B - Manual Agricultural/Natural Land Use Data Entry

4.1.4. Section C (Manual Commercial Properties Data Entry)

Section C is the manual entry section which gathers custom data on commercial properties. Values entered in this section indicate the number of commercial properties located within each sector at a maximum distance of one kilometre from the study location, an example of which is shown in Figure 4.10.

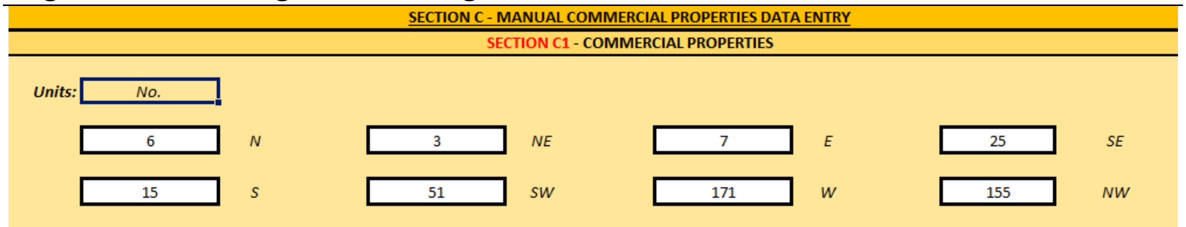


Figure 4.10: Section C - Manual Commercial Properties Data Entry

4.1.5. Section D (Manual Traffic Data Entry)

Section D is the manual entry section for the traffic variables and the amount of data required is dependent on the analysis type selected from the dropdown list in Section D1, shown in top left corner of Section D in Figure 4.11. The options in this dropdown are described in Section 4.1.1. The Conditional Formatting function has been employed to ensure that more data columns appear if the modeller decides to select one of the new model options, as shown in Figure 4.11.

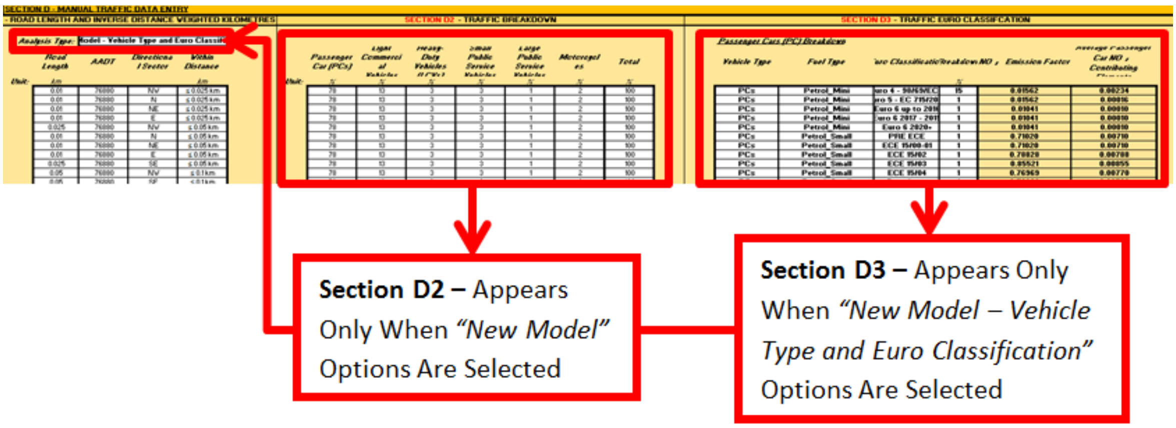


Figure 4.11: Section D - Alternating Tables Manual Traffic Data Entry

Section D1 is compulsory for all types of manual entry analysis. Here the modeller inputs data on the road and traffic network within 5 km of the study location. The required data includes all road lengths, AADT, direction relative to study location and distance to the road, as shown in Figure 4.12. The specified road lengths are the total lengths located within each sector. Values for every sector radius ranging from 25m to 5km are used to calculate the IDWVKT variable, but only entries up to a radius of 250m are considered for the road density variable (Naughton et al., 2018), as shown in Table 3.2.

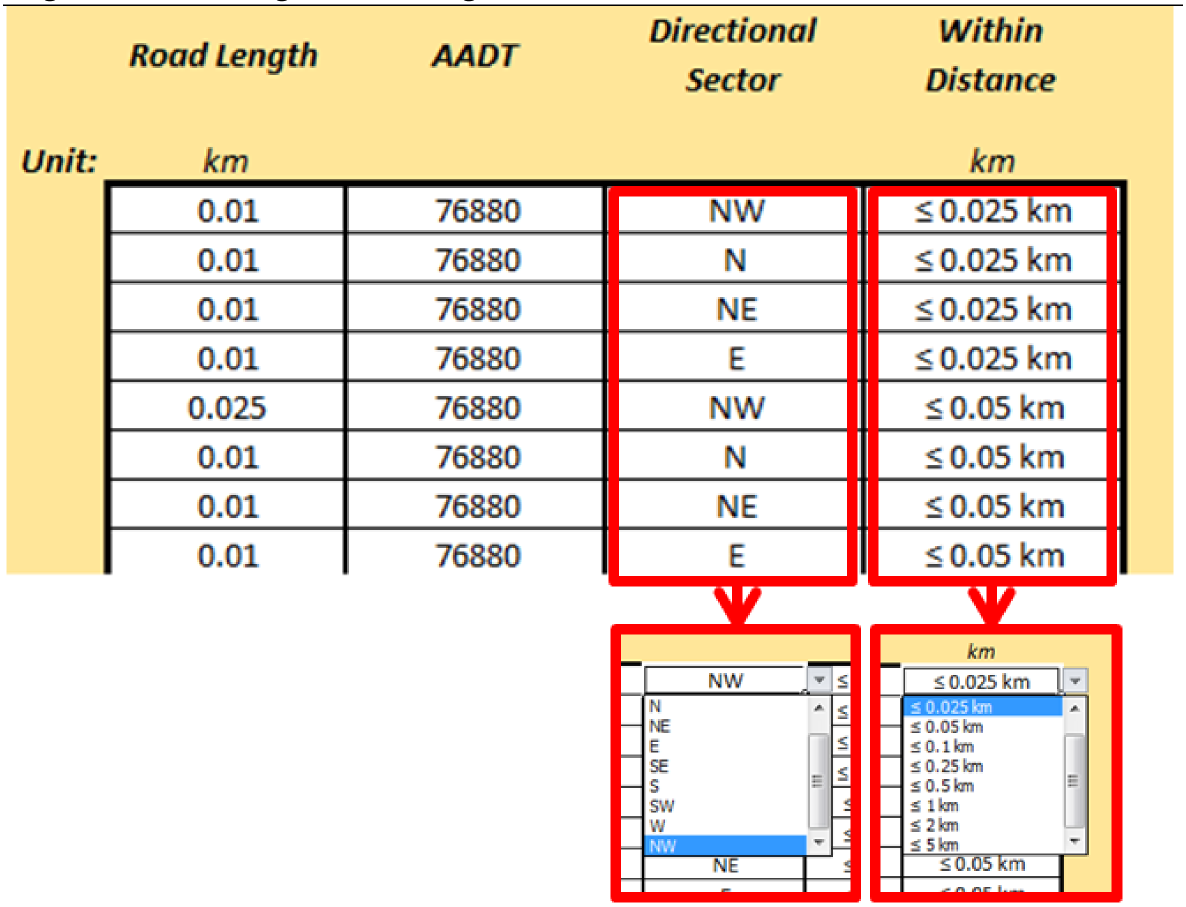
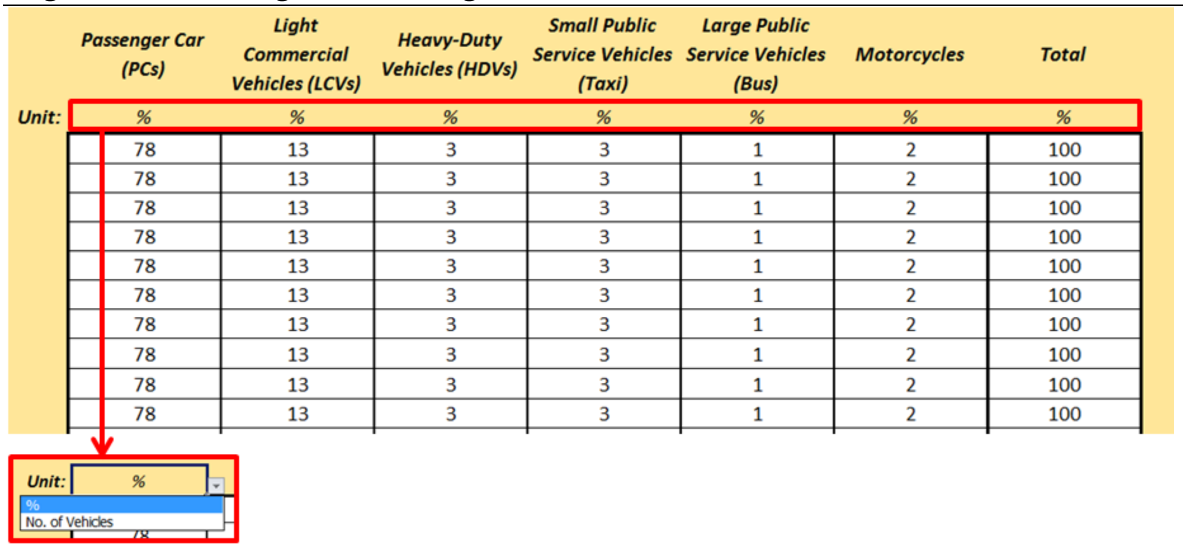


Figure 4.12: Section D1 - Manual Entry Traffic Data Network Details

Section D2 is applicable when the modeller opts to analyse the data using the new model methodology by applying the 2012 Euro Classification breakdown or by using an entirely new fleet breakdown definition. In this section, the modeller can define the number of vehicles in terms of a percentage of the AADT or as a number of vehicles, as shown in Figure 4.13. A TOTAL column is included to warn the modeller if the sum of the columns is not equal to the AADT entered in Section D1 or 100 if the values were entered as percentages.



	Passenger Car (PCs)	Light Commercial Vehicles (LCVs)	Heavy-Duty Vehicles (HDVs)	Small Public Service Vehicles (Taxi)	Large Public Service Vehicles (Bus)	Motorcycles	Total
Unit:	%	%	%	%	%	%	%
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100

Figure 4.13: Section D2 - Manual Entry Traffic Data (Traffic Breakdown)

Section D3 is only applicable if the modeller decides to define an entirely new vehicle fleet breakdown in a manual entry analysis. This section allows the modeller to select from a list of vehicle types, fuel types and Euro Classifications and assign percentages to create a custom vehicle fleet, as shown in Figure 4.14. The SUMPRODUCT function is used to search through the background data spreadsheets for a row which meets the criteria set for vehicle type, fuel type and Euro Class and return the NO_2 emission value. This function can search through a column to determine the row in that column which matches a specific criterion entered by the modeller and then return the value of a cell in the same row of an adjacent column. This function can be utilised for multiple criteria, in this case, finding a row which has a specific vehicle type, fuel type and Euro Class and returning the NO_2 emission value. The breakdown percentages are then multiplied by the NO_2 emission values and summed together to calculate the average NO_2 emission weighting for each category.

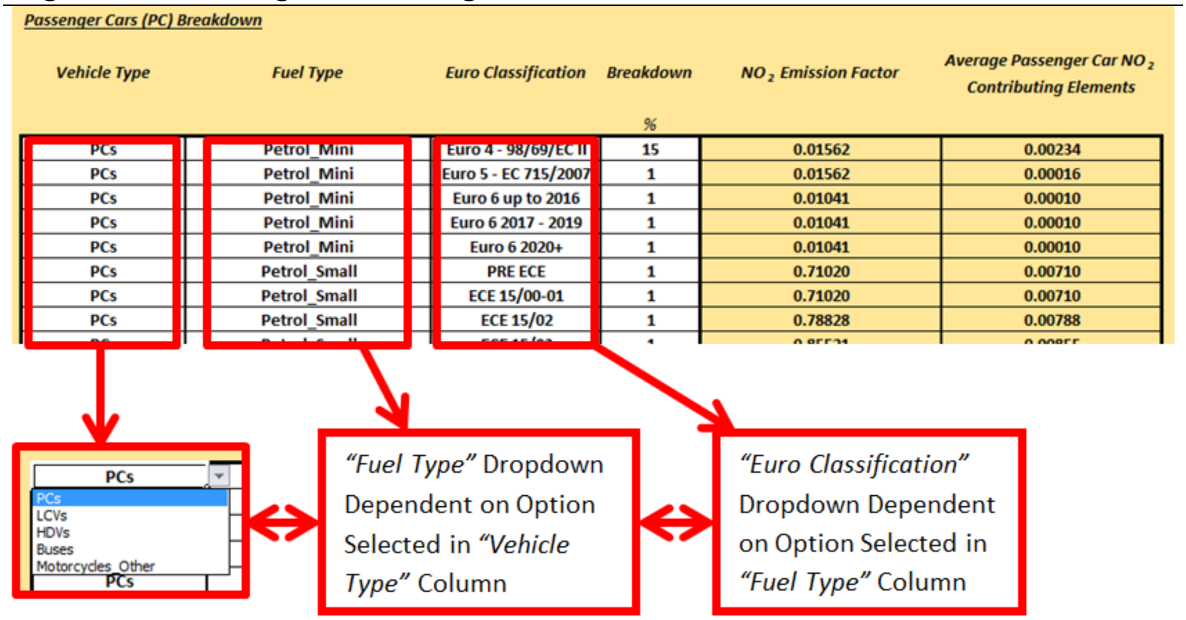


Figure 4.14: Section D3 - Manual Entry Traffic Data (Euro Classification)

4.2. Modeller Friendly Functions

Two methods of data input are employed by the model. The first is selection from a dropdown list, which appear once the cell is selected, as shown in Figure 4.15. This eliminates the risk of some errors such as incorrect spelling in cells requiring word inputs. A number of other cells may be dependent on these word input cells and therefore accurate text is essential for the model to operate correctly. In a number of cases, the modeller can identify the data and units which are acceptable for entries through this function.

The second method of modeller input is direct value entry which can be typed or copied from another file, as shown in Figure 4.16. These types of entries are used only in cases where numeric values are required, as an incorrect input in a numeric value entry would not be critical for model operation. Dropdown lists were created using the Data Validation – Settings – List function within Excel, which generates a dropdown within a cell based on the entries within another range of cells. All cells where input is required from the modeller are formatted with a thick border and clear background (as shown in Figure 4.16), which highlights the information yet to be completed by the modeller.

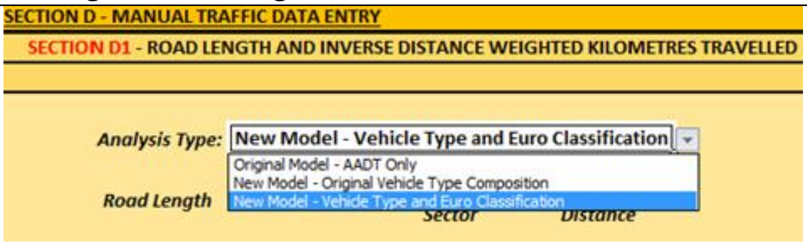


Figure 4.15: Model Dropdown Selection Feature

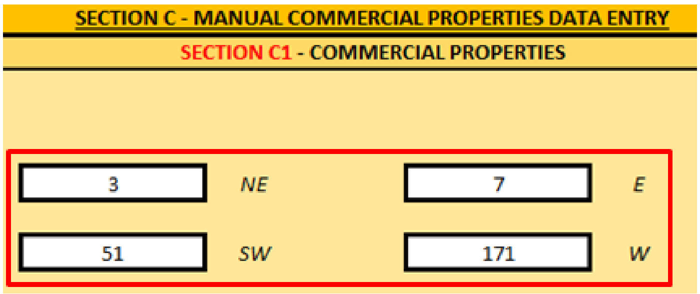
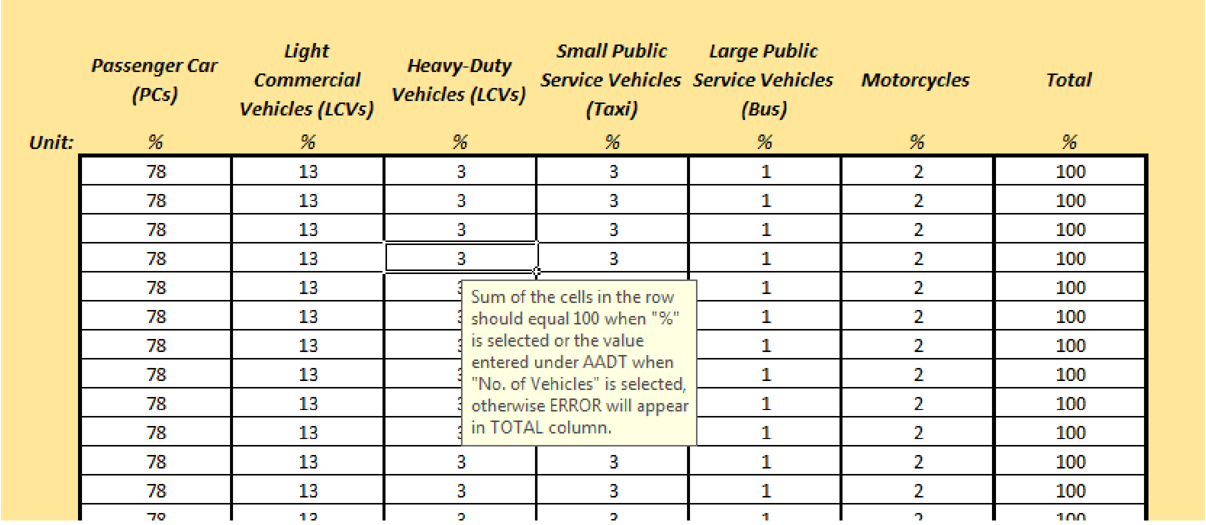


Figure 4.16: Mandatory Input Cell Formatting

A number of cells within the model have prompts / notes added to them so that when the cell is selected by the modeller; they are notified of the requirements that need to be met for the model to operate correctly, as shown in Figure 4.17. These notifications were created using the Data Validation – Input Message function, which generates notifications once the cell is selected by the modeller and reduces the amount of notes that are visible to the modeller once the cell is deselected.



	Passenger Car (PCs)	Light Commercial Vehicles (LCVs)	Heavy-Duty Vehicles (LCVs)	Small Public Service Vehicles (Taxi)	Large Public Service Vehicles (Bus)	Motorcycles	Total
Unit:	%	%	%	%	%	%	%
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100
	78	13			1	2	100
	78	13			1	2	100
	78	13			1	2	100
	78	13			1	2	100
	78	13			1	2	100
	78	13			1	2	100
	78	13	3	3	1	2	100
	78	13	3	3	1	2	100

Figure 4.17: Cell Notification / Prompt Feature

When the manual entry option is selected within the model, data relating to the dependent variables described previously in Section 3.1 must be provided. The model instructs the modeller on which data is required and guides the modeller to the appropriate data input spreadsheet / section, as shown in Figure 4.18. The Conditional Formatting function was used to clear the Year cell once the Manual Entry option was selected to avoid any possible confusion as to what year or time period that is being analysed by the model.

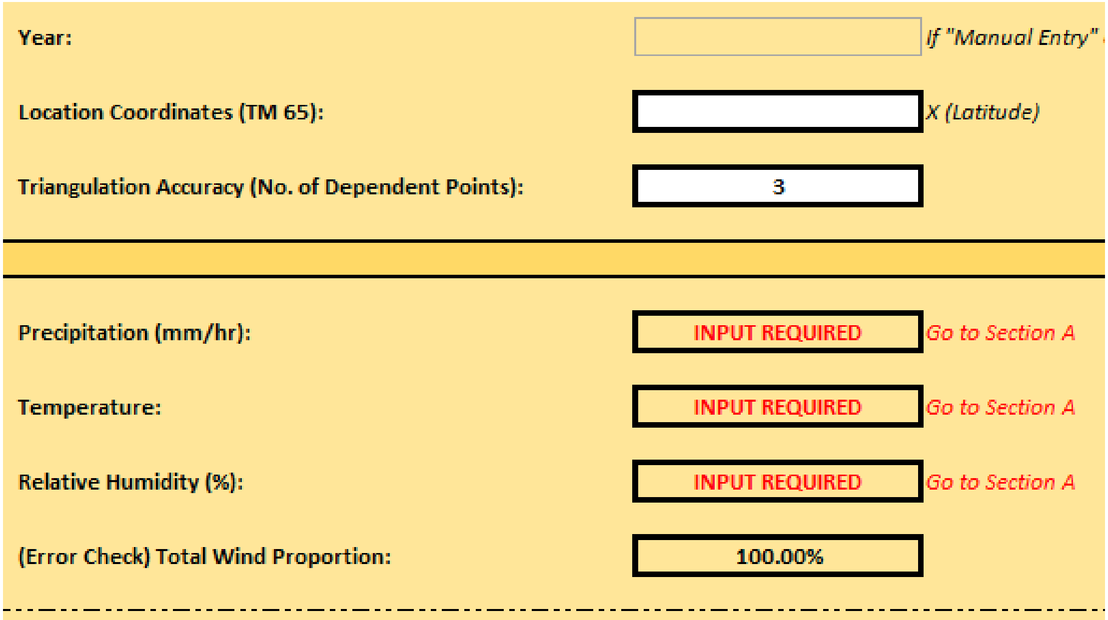


Figure 4.18: Mandatory Data Input Notification / Prompt

4.3. NO_2 Concentration Calculation Process

Once the modeller selects their preferred analysis type (pre-set year approach or manual entry approach) and enters all the required data in the sections described above, the values for all the parameters in the WS-LUR model equation, shown in Equation 4.1 below, are displayed on the Input Sheet (example shown below in Figure 4.19).

$$C = \alpha_0 + \sum_{i=1}^{8} \sum_{j=1}^{M} Wf_i \, \alpha_j P_j$$

Eqn. 4.1: WS-LUR Concentration Formula and IDWVKT Variable

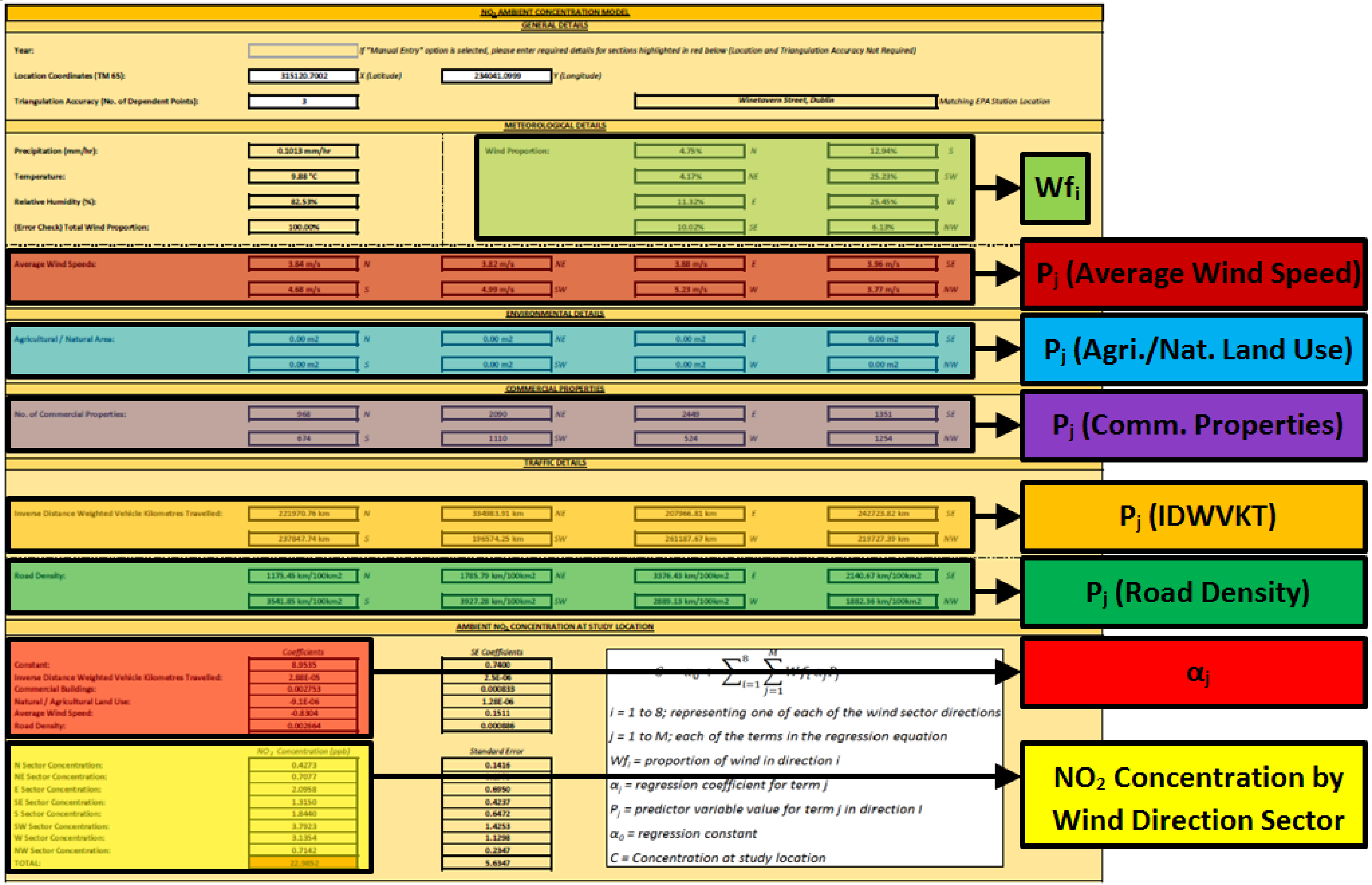


Figure 4.19: Input Sheet Calculation Example

The following figures and calculations show the process of calculating the ambient NO_2 concentration for a location. The values for the Wf_i factor for each wind direction sector are found in the Wind Proportion section of the Input Sheet, as shown in Figure 4.20.

Wind Proportion:	4.75%	N	12.94%	S
	4.17%	NE	25.23%	SW
	11.32%	E	25.45%	W
	10.02%	SE	6.13%	NW

Figure 4.20: Wf_i Factor / Wind Proportion Section

The values for the P_j term for each of the predictor variables in each of the wind direction sectors are found in the next few sections of the Input Sheet, as shown in Figure 4.21.

Average Wind Speeds:	3.84 m/s	N	3.82 m/s	NE	3.88 m/s	E	3.96 m/s	SE
	4.68 m/s	S	4.99 m/s	SW	5.23 m/s	W	3.77 m/s	NW
Agricultural / Natural Area:	0.00 m2	N	0.00 m2	NE	0.00 m2	E	0.00 m2	SE
	0.00 m2	S	0.00 m2	SW	0.00 m2	W	0.00 m2	NW
No. of Commercial Properties:	968	N	2090	NE	2449	E	1351	SE
	674	S	1110	SW	524	W	1254	NW
Inverse Distance Weighted Vehicle Kilometres Travelled:	221970.76 km	N	334983.91 km	NE	207966.81 km	E	242723.82 km	SE
	237847.74 km	S	196574.25 km	SW	261187.67 km	W	219727.39 km	NW
Road Density:	1175.45 km/100km2	N	1785.79 km/100km2	NE	3376.43 km/100km2	E	2140.67 km/100km2	SE
	3541.85 km/100km2	S	3927.28 km/100km2	SW	2889.13 km/100km2	W	1882.36 km/100km2	NW

Figure 4.21: P_j Term - Average Wind Speed, Agricultural/Natural Area, Commercial Properties, IDWVKT and Road Density Values

The next section of the Input Sheet shows the values for the α_0 (constant) and α_j terms (regression coefficients) within the WS-LUR equation, as shown in Figure 4.22.

	Coefficients
Constant:	8.9535
Inverse Distance Weighted Vehicle Kilometres Travelled:	2.88E-05
Commercial Buildings:	0.002753
Natural / Agricultural Land Use:	-9.1E-06
Average Wind Speed:	-0.8304
Road Density:	0.002664

Figure 4.22: Regression Coefficient Values, α_j and α_0 Terms

A summary of the NO_2 contribution by wind direction sector and total NO_2 concentration for a study location is provided at the bottom of the Input Sheet, which identifies the direction(s) which contribute most of the NO_2 at a location, as shown in Figure 4.23.

	NO_2 Concentration (ppb)
N Sector Concentration:	0.4273
NE Sector Concentration:	0.7077
E Sector Concentration:	2.0958
SE Sector Concentration:	1.3150
S Sector Concentration:	1.8440
SW Sector Concentration:	3.7923
W Sector Concentration:	3.1354
NW Sector Concentration:	0.7142
TOTAL:	22.9852

Figure 4.23: Total NO_2 Concentration / NO_2 Concentration by Wind Sector

The following calculations show the process the modeller could utilise to identify the NO_2 contribution in one wind directional sector or the contribution by variable within the model. Isolating all the predictor variable values / regression coefficients in one directional sector would produce the NO_2 contribution from that directional sector, as shown in the following calculation (values sourced from the figures above):

$$North\ Directional\ Sector\ NO_2\ Concentration$$
$$= Wf_N(\alpha_{WS}P_{WS,N} + \alpha_{NAT}P_{NAT,N} + \alpha_{COM}P_{COM,N} + \alpha_{ID}P_{ID,N} + \alpha_{RD}P_{RD,N})$$

Where:

Wf_N = Wind Proportion for North Sector

α_{WS} = Average Wind Speed Regression Coefficient

α_{NAT} = Agricultural / Natural Land Use Area Regression Coefficient

α_{COM} = Commercial Properties Regression Coefficient

α_{ID} = IDWVKT Regression Coefficient

α_{RD} = Road Density Regression Coefficient

$P_{WS,N}$ = Average Wind Speed in North Sector

$P_{NAT,N}$ = Agricultural / Natural Land Use Area in North Sector

$P_{COM,N}$ = Commercial Properties in North Sector

$P_{ID,N}$ = IDWVKT in North Sector

$P_{RD,N}$ = Road Density in North Sector

$$North\ Directional\ Sector\ NO_2\ Concentration = 0.0475\big((-0.8304x3.84) + (-9.1x10^{-6}x0) + (0.002753x968) + (2.88x10^{-5}x221970.76) + (0.002664x1175.45)\big) \approx 0.428\ ppb$$

Isolating all the values for one predictor variable would identify the NO_2 contribution from one variable, as shown by the following calculation (example based on the commercial properties for the location in the figures above):

$$Commercial\ Properties\ NO_2\ Concentration = \alpha_{COM}(Wf_N P_{COM,N} + Wf_{NE} P_{COM,NE} + Wf_E P_{COM,E} + Wf_{SE} P_{COM,SE} + Wf_S P_{COM,S} + Wf_{SW} P_{COM,SW} + Wf_W P_{COM,W} + Wf_{NW} P_{COM,NW})$$

Where:

Wf_{NE} = Wind Proportion for Northeast Sector

Wf_E = Wind Proportion for East Sector

Wf_{SE} = Wind Proportion for Southeast Sector

Wf_S = Wind Proportion for South Sector

Wf_{SW} = Wind Proportion for Southwest Sector

Wf_W = Wind Proportion for West Sector

Wf_{NW} = Wind Proportion for Northwest Sector

$P_{COM,NE}$ = Commercial Properties in Northeast Sector

$P_{COM,E}$ = Commercial Properties in East Sector

$P_{COM,SE}$ = Commercial Properties in Southeast Sector

$P_{COM,S}$ = Commercial Properties in South Sector

$P_{COM,SW}$ = Commercial Properties in Southwest Sector

$P_{COM,W}$ = Commercial Properties in West Sector

$P_{COM,NW}$ = Commercial Properties in Northwest Sector

$$Commercial\ Properties\ NO_2\ Concentration = 0.002753\big((0.0475x968) + (0.0417x2090) + (0.1132x2449) + (0.1002x1351) + (0.1294x674) + (0.2523x1110) + (0.2545x524) + (0.0613x1254)\big) = 3.09\ ppb$$

The effect of the emission weightings on IDWVKT is factored into the values shown in the Input Sheet and if the modeller selects the manual entry option, the emission weightings are based on the vehicle fleet breakdown defined by the modeller in Section D of the model. Table 4.1 shows an example of the effect that the emission weightings can have on the IDWVKT variable in comparison to the original model methodology.

Table 4.1: IDWVKT Original Model / New Model B Differences

Euro Classification	Original Model IDWVKT	Vehicle Emission Weighting	New Model B IDWVKT
Cars	200 000	0.7	140 000
LGVs	20 000	1.8	36 000
HGVs	5 000	3	15 000
SPSVs	1 000	1.5	1 500
LPSVs	2 000	3.5	7 000
Motorcycles	500	0.4	200
Total	228 500		199 700

4.4. Conclusion

This chapter introduced the key features of the WS-LUR model that was developed within Excel. This included a step-by-step process of calculating the ambient NO_2 concentration at a location using one of two approaches available to the modeller. The first is the pre-set approach which allows the modeller to identify a location, by specifying the co-ordinates of the location and selecting one of the pre-set years, between 2016 and 2018, and the model automatically calculates the concentration for that location using data that is in the background of the model. The second approach is the manual entry option where the modeller must go through a number of sections within the model and input all the statistics relating to each of the variables in the WS-LUR model to generate the modelled concentration. Details of the manual entry sections within the WS-LUR model were also introduced with Section A covering meteorological details, Section B covering land use data, Section C covering commercial properties data and Section D covering traffic data (IDWVKT and road density).

The pre-set approach was used to re-validate the Original Model Methodology and validate the New Model Methodologies, which utilised the data collected and analysed as described in Chapter 3. The results of the above model validations are covered in Section 5.1.2 of the following chapter. A comparison of measured and modelled concentrations was also carried out using the pre-set approach. The measured concentrations from EPA monitoring stations within the Leinster and Monaghan region were compared with modelled concentrations from each of the model methodologies (Original, New Model A and New Model B) and results of this analysis are provided in Section 5.1.3.

The manual entry approach was used to analyse the performance of the New Model B Methodology in a unique scenario / environment, such as the 1st COVID lockdown period. A number of comparisons were carried out using the manual entry approach, such as comparison of measured and modelled concentrations during the COVID lockdown, comparison of measured and modelled differences between pre-COVID and COVID concentrations and an analysis of each predictor variable and the respective changes in concentration under COVID conditions. Methodology, data sources and results of this analysis are provided in Sections 5.2 and 5.3.

A number of modeller friendly functions were included in the model and details of these functions were also introduced in this chapter. These include dropdown lists (removes potential typo errors or incorrect value entries), formatting of cells (can easily identify input cells), cell notifications / prompts (provide direction to the modeller as to the values required in cells) and adjustable units for data entry.

5. Integrated Transportation and Land Use NO_2 Model Validation

The validation of the enhanced WS-LUR model, including the use of transportation model data to calculate location- and time-specific vehicle emission data, is presented in this chapter. This validation and the investigation of model accuracy is carried out in two ways.

First, the capability of the new model methodologies to calculate ambient NO_2 concentrations whilst retaining the accuracy of the original model is evaluated. This is done by comparing measured concentrations with modelled concentrations using both the original model and the new model methodologies for three pre-set years (2016 to 2018). The objectives of this analysis were to:

- Re-validate the Original Model due to the length of time passed since the original study analysis by comparing modelled results with measured concentrations;
- Validate the New Model Methodologies against the Original Model and measured concentrations to ensure the accuracy of the Original Model is retained with the inclusion of vehicle emission weightings in the IDWVKT variable;

Second, the accuracy of the new model during unique scenarios and / or environments was explored by looking at the 1st COVID lockdown period (28th March 2020 to 17th May 2020). The procedure and results of an analysis carried out using the enhanced WS-LUR model developed in Chapter 3 are presented. The objectives of this analysis were to:

- Characterise the meteorological, source locations and traffic conditions during the 1st COVID lockdown period;
- Model NO_2 concentrations at various locations during this period;
- Evaluate the capability of the WS-LUR model to calculate changes in ambient NO_2 concentrations for unique scenarios;
- Based on performance of the model in this scenario, identify the effect of individual parameter changes experienced during the COVID lockdown on ambient NO_2 concentrations and the potential NO_2 reductions that can be achieved by mitigation measures which target these parameters.

5.1. Model Validation Study (Pre-Set Years (2016 to 2018) Analysis Results)

This section contains results for the vehicle emission weightings, which are applied to the IDWVKT variable in the New Model methodologies. Re-validation of the Original Model and validation of the New Model methodologies are introduced by comparing modelled concentrations with measured concentrations at multiple locations. It also confirms the link between the New Model methodologies and the Original Model is retained, whilst adding the ability to investigate mitigation measures within the model; such as targeting the vehicle fleet breakdown. Data and methodology used to generate the following results were introduced in Section 3.3 and utilised the pre-set year approach within the model described in Chapter 4.

5.1.1. Unit Vehicle NO_2 Emissions

The analysis of the vehicle fleet breakdown, described in Section 3.3.5, identified major changes in the average emissions by vehicle type, as well as the average emissions from a vehicle, between the vehicle fleet in the original model period considered by Naughton et al. (2010 to 2012) and the vehicle fleets in the model years considered in this study. The results of this analysis are presented in Table 5.1. The emissions from the average vehicle were 25.7% to 27.9% higher in 2016 – 2018 in comparison to the emissions from the average vehicle in the original study period. The major contributors to this increase were PCs, which had on average 44.4% to 46.8% higher emissions per kilometre than in 2010 – 2012. The increase in average emissions for PCs was due to the increase in the number of diesel vehicles in the fleet. Moderate increases were also experienced in the LCVs and SPSVs categories, with 9.4% - 14.2% and 4.9% - 12.6% increases respectively. HDVs and LPSVs are both mainly diesel fuelled vehicles and large increases in total vehicle numbers within these categories were experienced between 2016 and 2018. Total HDVs increased by 7.3%, 9.4% and 11.3% in 2016, 2017 and 2018 respectively in comparison to 2010 – 2012 and total LPSVs also increased by 19.1%, 25.5% and 32.5% between 2016 and 2018 in comparison to the original study period. Average NO_2 emissions reduced by 28.1% - 43.2% for HDVs and 32.3% - 49.1% for LPSVs by 2016 – 2018 in comparison to the original study period. The main contributing factor to the decrease in average emissions is the increase in Euro VI vehicles within the fleet between 2016 and 2018. Average emissions from motorcycles also moderately decreased from 2012 onwards, with decreases of 12.4%, 13.7% and 14.9% in comparison to the original study period.

Table 5.1: Average NO_2 Emission Rates and Percentage Change in Comparison to 2010 – 2012 by Vehicle Type and Year

Year / Monitoring Station	Original Model (2010 – 2012)	2016	2017	2018
PCs	0.082 g/km	0.118 g/km +44.4%	0.120 g/km +46.8%	0.119 g/km +46.2%
LCVs	0.288 g/km	0.322 g/km +12.0%	0.329 g/km +14.2%	0.315 g/km +9.4%
HDVs	0.400 g/km	0.288 g/km -28.1%	0.258 g/km -35.6%	0.227 g/km -43.2%
SPSVs	0.165 g/km	0.185 g/km +12.6%	0.180 g/km +9.3%	0.173 g/km +4.9%
LPSVs	0.845 g/km	0.572 g/km -32.3%	0.501 g/km -40.7%	0.430 g/km -49.1%
Motorcycles	0.009 g/km	0.008 g/km -12.5%	0.008 g/km -13.7%	0.007 g/km -14.8%
Average Vehicle	0.114 g/km	0.146 g/km +26.6%	0.148 g/km +27.9%	0.145 g/km +25.7%

The NO_2 emission weightings (concept introduced in Section 3.2) for each vehicle type in each of the years / time period were calculated using Equation 5.1. The use of the average emission from all vehicles retains the link with the original model methodology whilst introducing a system which applies a weighting to the IDWVKT variable based on the average emission rate from the respective vehicle types.

$$NO_2\ Emission\ Weighting = {}^{e_v}/_{e_A}$$

Eqn. 5.1: NO_2 Emission Weighting

Where:

e_V = Average emission from vehicle type v in a study period

e_A = Average emission from all vehicles in a study period

The average vehicle and average PC, LCV, HDV and SPSV emitted more NO_2 between 2016 and 2018 in comparison to the original model time period, 2010 – 2012, as shown in Table 5.1. This led to an increase in the emissions from the average vehicle. As expected, the PC Emission Weighting increased due to the increased emissions from the average PC, as shown in Table 5.2, but the other vehicle types (LCV and SPSV) all experienced minor reductions in the Emission Weighting despite increased average emissions. The increase in emission rates for the respective vehicle types was outweighed by the increase in emissions from the average vehicle, which resulted in minor reductions in weightings for the LCVs and SPSVs. Changes in PC emission rates affect the average vehicle emission rate considerably more than the other vehicle types as there are substantially more PCs in the national vehicle fleet.

Table 5.2 shows the weightings for all vehicle types, which were then applied to the IDWVKT for the respective vehicle types. The PC Emission Weighting for the original study period was 0.7 and due to the increased emission rates had a weighting of approximately 0.8 between 2016 and 2018. As discussed above, despite increased emission rates for LCVs and SPSVs, which had Emission Weightings of 2.5 and 1.4 respectively during the original study period, the weightings reduced to 2.2 and 1.2 respectively between 2016 and 2018. The largest decreases in Emission Weightings were in the HDV and LPSV fleet, which reduced from 3.5 and 7.4 to approximately 1.7 and 3.4 respectively since the original study period. This was due to the substantial transition from older Euro Classes in these vehicle types, as discussed in Section 3.3.5.4.

Table 5.2: NO_2 Emission Weightings by Vehicle Type and Year

Vehicle Type	Original Model (2010 – 2012)	2016	2017	2018
PCs	0.712	0.803	0.808	0.821
LCVs	2.515	2.199	2.219	2.170
HDVs	3.498	1.963	1.742	1.568
SPSVs	1.439	1.265	1.216	1.191
LPSVs	7.381	3.900	3.380	2.966
Motorcycles	0.076	0.052	0.051	0.051

5.1.2. Model Validation

To validate the model, the NO_2 concentrations calculated in the original study by Naughton et al. (2018) were compared with those calculated using the new model, which accounts for the vehicle fleet breakdown, assuming that the traffic conditions for the study location (vehicle type breakdown and Euro class breakdown) match the traffic conditions in the original period. Table 5.3, Table 5.4, Table 5.5 and Table 5.6 identify the NO_2 emission weighting and vehicle type breakdown for each vehicle type in each of the pre-set years / time period. The resultant weightings in the tables below, represent the overall weighting applied to the IDWVKT variable. Therefore, if this value is equal to 1, which mainly occurs in areas where the vehicle fleet breakdown on a route is equal to the national vehicle fleet, the value of the IDWVKT variable is the same in both the original and new model methodologies. This provides a direct comparison of the concentration results obtained with the original and new models while introducing sufficient detail to identify particular vehicle types which can contribute to elevated concentrations at a given location.

Table 5.3: Original Model Period 2010 - 2012 Model Validation

Vehicle Type	NO_2 Emission Weighting	Vehicle Type Breakdown	NO_2 Emission Weighting x Vehicle Type Breakdown
PCs	0.712	82.85%	0.590
LCVs	2.515	12.81%	0.322
HDVs	3.498	1.24%	0.043
LPSVs	7.381	0.36%	0.027
Motorcycles	0.076	1.61%	0.001
SPSVs	1.439	1.12%	0.016
Electric Vehicles	0	0.01%	0
Resultant Weighting			1

Table 5.4: Original Model Period 2016 Model Validation

Vehicle Type	NO_2 Emission Weighting	Vehicle Type Breakdown	NO_2 Emission Weighting x Vehicle Type Breakdown
PCs	0.803	83.05%	0.667
LCVs	2.199	12.59%	0.277
HDVs	1.963	1.44%	0.028
LPSVs	3.900	0.40%	0.016
Motorcycles	0.052	1.56%	0.001
SPSVs	1.265	0.89%	0.011
Electric Vehicles	0	0.07%	0
Resultant Weighting			1

Table 5.5: Original Model Period 2017 Model Validation

Vehicle Type	NO_2 Emission Weighting	Vehicle Type Breakdown	NO_2 Emission Weighting x Vehicle Type Breakdown
PCs	0.808	82.97%	0.670
LCVs	2.219	12.57%	0.279
HDVs	1.742	1.46%	0.026
LPSVs	3.380	0.42%	0.014
Motorcycles	0.051	1.60%	0.001
SPSVs	1.216	0.86%	0.010
Electric Vehicles	0	0.11%	0
Resultant Weighting			1

Table 5.6: Original Model Period 2018 Model Validation

Vehicle Type	NO_2 Emission Weighting	Vehicle Type Breakdown	NO_2 Emission Weighting x Vehicle Type Breakdown
PCs	0.821	82.94%	0.681
LCVs	2.170	12.53%	0.272
HDVs	1.568	1.48%	0.023
LPSVs	2.966	0.43%	0.013
Motorcycles	0.051	1.58%	0.001
SPSVs	1.191	0.84%	0.010
Electric Vehicles	0	0.19%	0
Resultant Weighting			1

The NO_2 Emission Weightings are applied to the IDWVKT of the respective vehicle types, which increases the IDWVKT if the vehicle type emits more than the unit vehicle and reduces the IDWVKT if the vehicle type emits less than the unit vehicle, as described in Section 3.2. These weightings are pre-calculated if the modeller uses the pre-set year approach or if the manual entry approach is selected, they are calculated once Section D3 of the model is completed, as described in Chapter 4.

5.1.3. Measured and Modelled Concentration Comparisons

The limitation in available traffic data, which was only available for the eastern region of Ireland (Leinster and parts of Ulster) affected the scope of the model validation. Within the eastern region, a total of 38 NO_2 measurements obtained at 16 different EPA monitoring sites over a 3 year period were analysed to compare measured concentrations with original model methodology results and results from two variations of the new model methodology. Continuous monitors were installed at these locations and ensured larger coverage of measurements throughout the year with only short periods of inactivity for maintenance purposes. NO_2 measurement data was made available by the EPA through the Secure Archive for Environmental Research (SAFER) database (Environmental Protection Agency, 2019) in excel format and contained hourly measurements for a calendar year. The hourly measurement data was analysed to determine the annual average daily concentrations recorded at each of these locations.

Measured concentrations were within the standard error range of the model for 50% of observations (19 measurements) using the original model methodology, 42.1% (16 measurements) using the New Model A methodology and 47.4% (18 measurements) using the New Model B methodology, as shown in Figure 5.1, Figure 5.2 and Figure 5.3. Figure 5.1 shows the measured concentrations and all variations of modelled concentrations with standard error ranges (Original Model, New Model A and New Model B Methodologies) for all monitoring station locations in 2018 whilst Figure 5.2 and Figure 5.3 show measured concentrations and standard error ranges for 2017 and 2016 respectively. The standard error ranges were calculated using the same equation as the modelled NO_2 concentrations (Equation 3.1) except different regression coefficients were used, which are also shown in Table 3.2. In the original study (Naughton et al., 2018), 68% of the measured concentrations were within the standard error range of the modelled concentrations. However, even as the sample size has remained similar to the original study (16 locations compared to 15 locations) the locations have changed considerably with only 9 of the original 15 locations included in the 2016 to 2018 comparison. Moreover, 5 of these stations were located in close proximity in the Greater Dublin Area, which limited an analysis of spatial (land use and meteorological) and temporal (traffic) variability for locations included in the original study. The expansion of the EPA air quality monitoring network since the original study introduced six new locations within the Leinster region (province covered by this analysis); one rural station, two stations in towns outside of Dublin and three stations within the Greater Dublin Area, which improved the analysis of spatial and temporal variability of the model.

In any distribution of data, approximately 95% of the data points should be within the double standard error ranges (University of Pennsylvania, Penn Arts & Sciences, 2021; Statology, 2019) and approximately 95% (94.74%) of data points complied with this requirement in the Original Model and New Model B methodologies as shown in Figure 5.4, Figure 5.5 and Figure 5.6. Figure 5.4 shows the measured concentrations and all variations of modelled concentrations with double standard error ranges (Original Model, New Model A and New Model B Methodologies) for all monitoring station locations in 2018 whilst Figure 5.5 and Figure 5.6 show measured concentrations and double standard error ranges for 2017 and 2016 respectively. The New Model A methodology captured 97.37% of data points when considering the double standard error ranges.

The model typically overestimated the NO_2 concentrations for all model methodologies, but there were two instances where the model underestimated, both in 2018 at St. John's Road and Ringsend, as shown in Figure 5.1. This was the first year the St. John's Road monitoring site was active; further sampling at this site would confirm that there are other factors, not captured by the model, which contribute to NO_2 concentrations. Factors which were identified at this site that may contribute to NO_2 pollution but are not covered by the variables within the model include train traffic entering and leaving Heuston train station, numerous areas where engine idling could occur such as taxi ranks and bus stops and a traffic signalised junction / crossing where queuing and lower traffic speeds are common. The Ringsend monitoring site was only active in 2017 and 2018 during the study period. In 2017 the measured values agreed well with the modelled concentrations, whilst in 2018, they were marginally outside the standard error range, as shown in Figure 5.1 and Figure 5.2. The meteorological conditions changed considerably from 2017 to 2018 with approximately 59% of the wind coming from a west / south-westerly direction and 16%

from an east / south-easterly direction in 2017 compared to 45% west / south-westerly and 23.5% east / south-easterly proportions in 2018, and this change may have influenced the averaged measured concentration. Potential sources of NO_2 near the Ringsend station not captured by the model include the Poolbeg Generating Station, boat traffic entering Dublin Port and vehicular traffic such as HGVs in Dublin Port (ESB Energy International, 2013; European Space Agency, 2020). Traffic within Dublin Port is not captured as it is not part of the local authority or Transport Infrastructure Ireland road network.

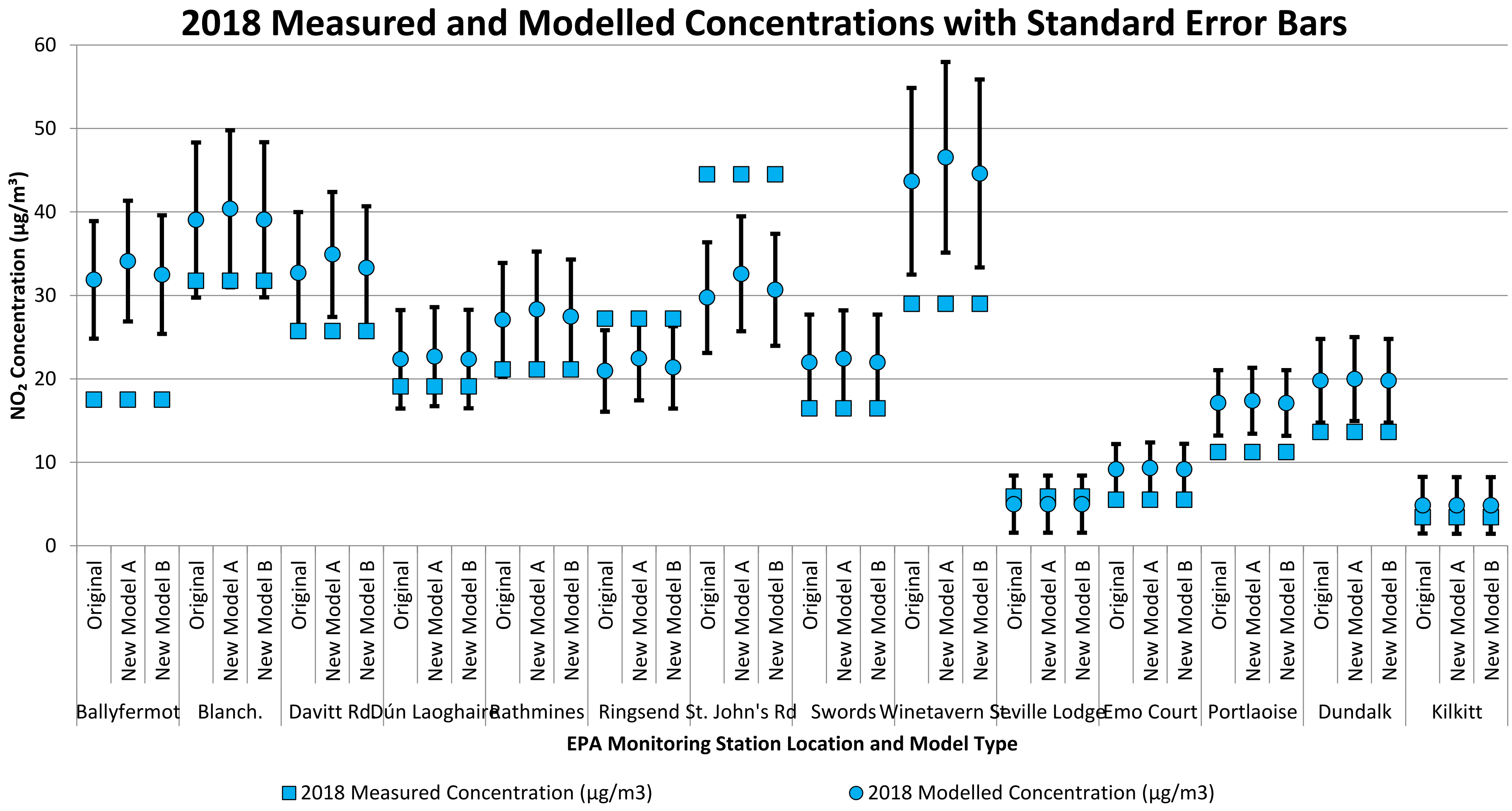


Figure 5.1: 2018 Measured and Modelled NO_2 Concentrations with Standard Error High-Low Bars

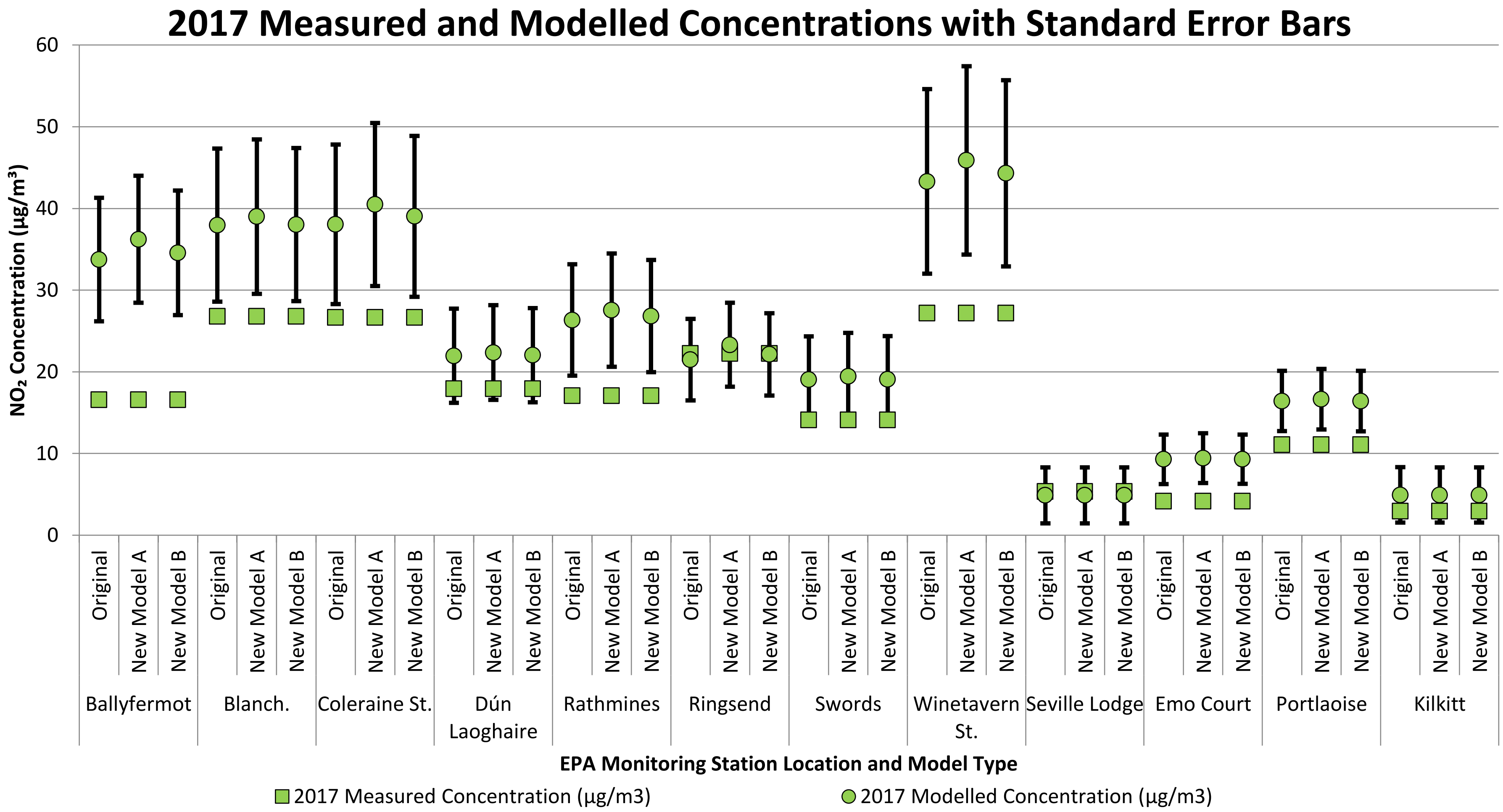


Figure 5.2: 2017 Measured and Modelled NO_2 Concentrations with Standard Error High-Low Bars

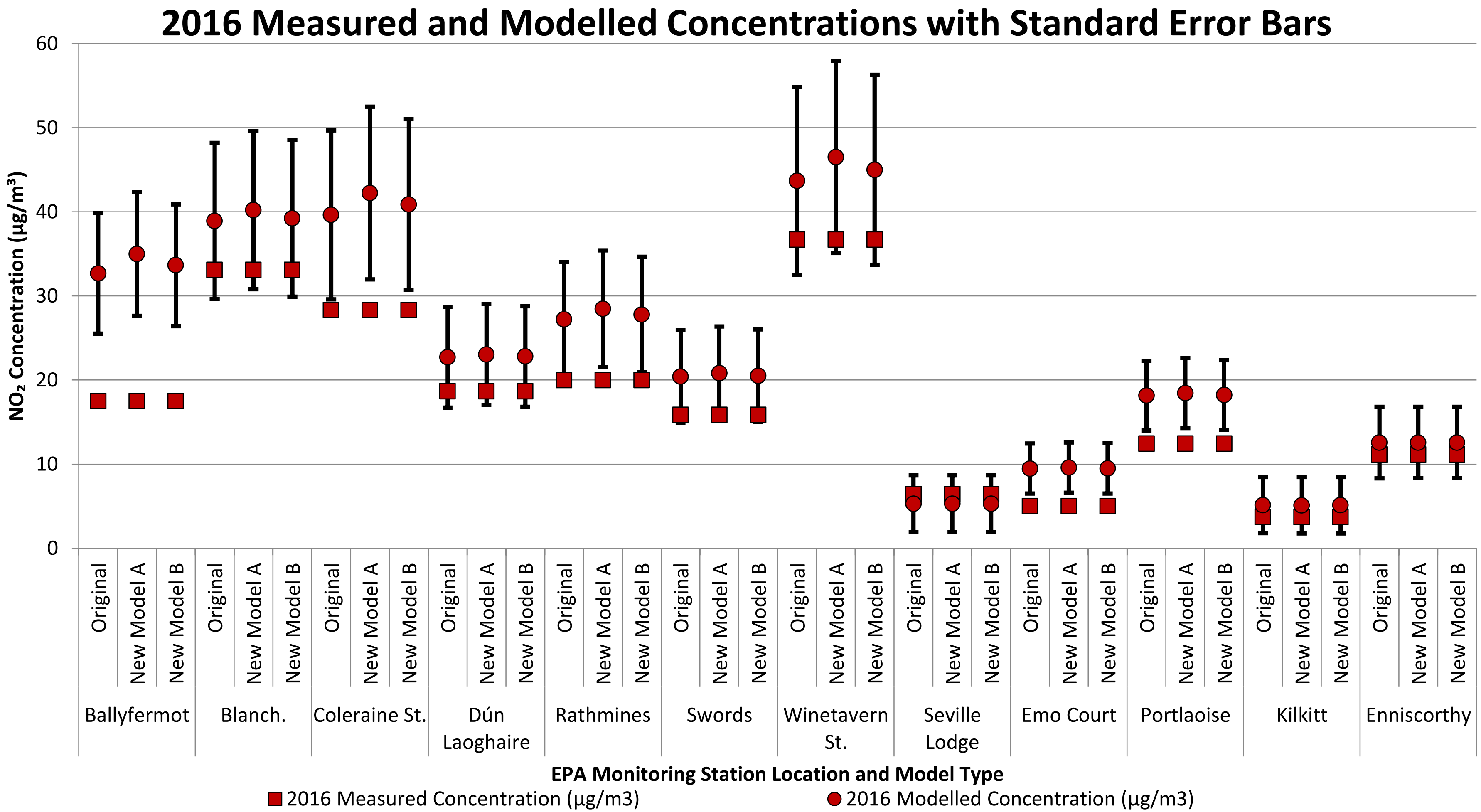


Figure 5.3: 2016 Measured and Modelled NO_2 Concentrations with Standard Error High-Low Bars

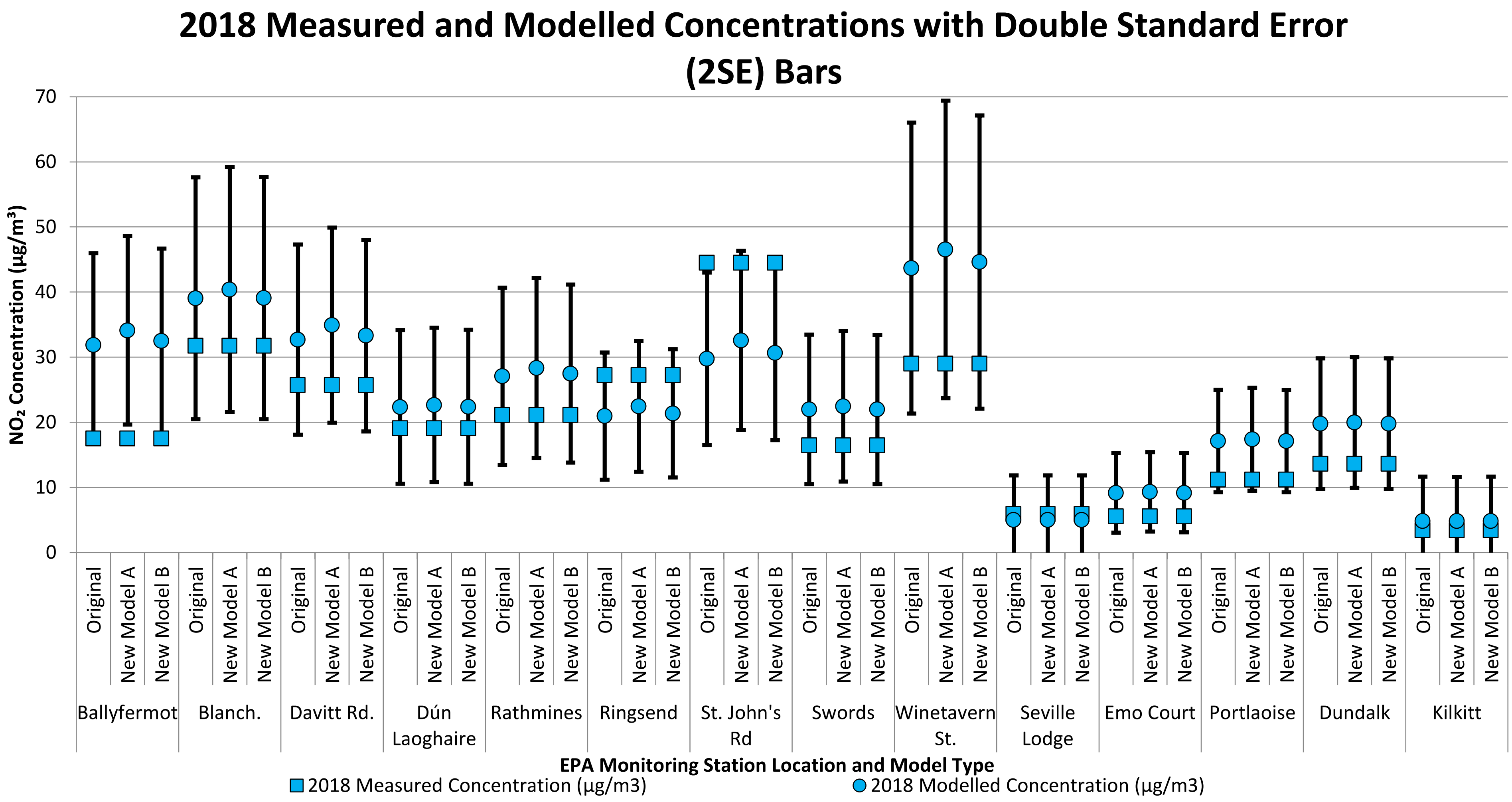


Figure 5.4: 2018 Measured and Modelled NO_2 Concentrations with Double Standard Error (2SE) High-Low Bars

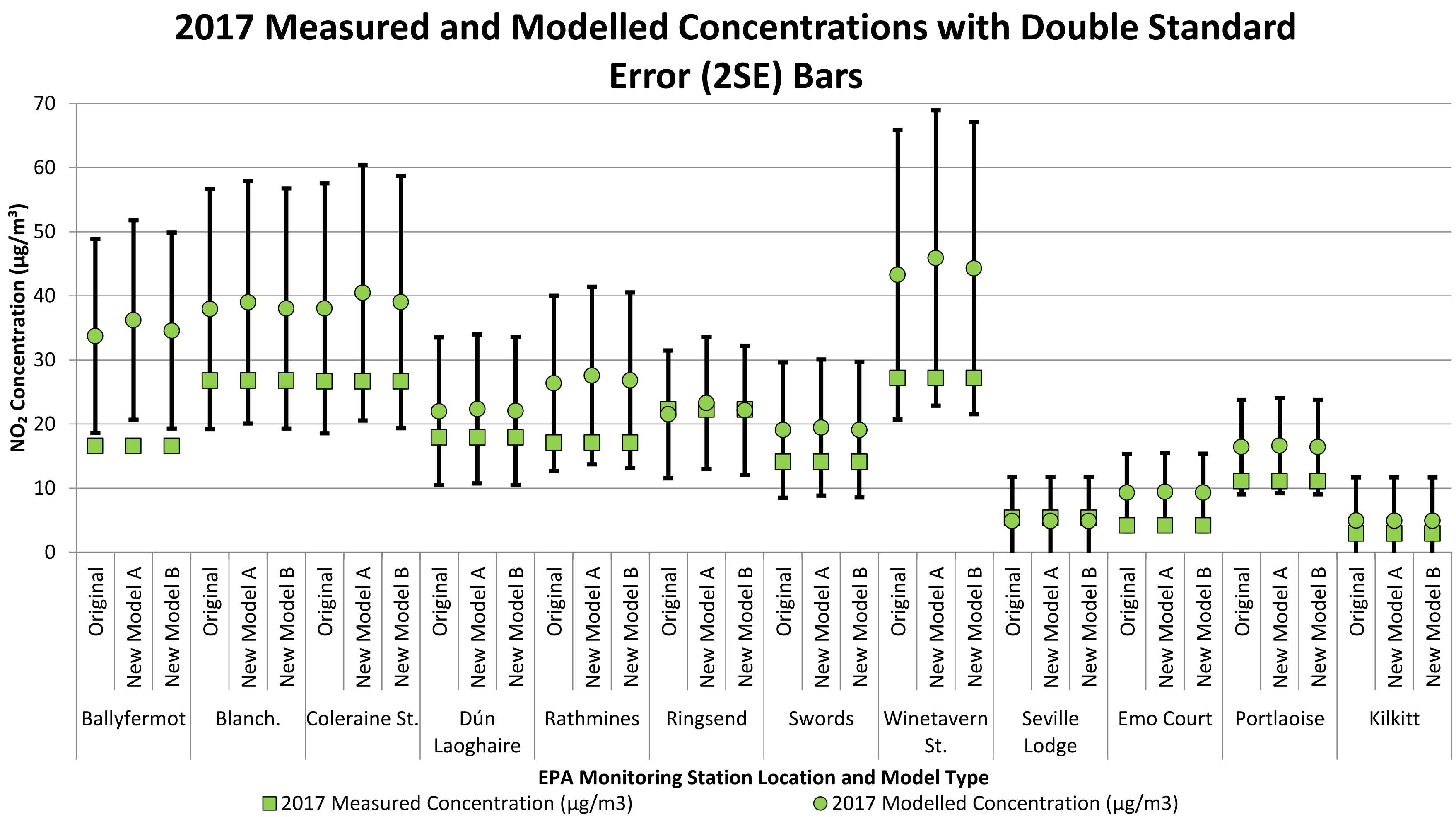


Figure 5.5: 2017 Measured and Modelled NO_2 Concentrations with Double Standard Error (2SE) High-Low Bars

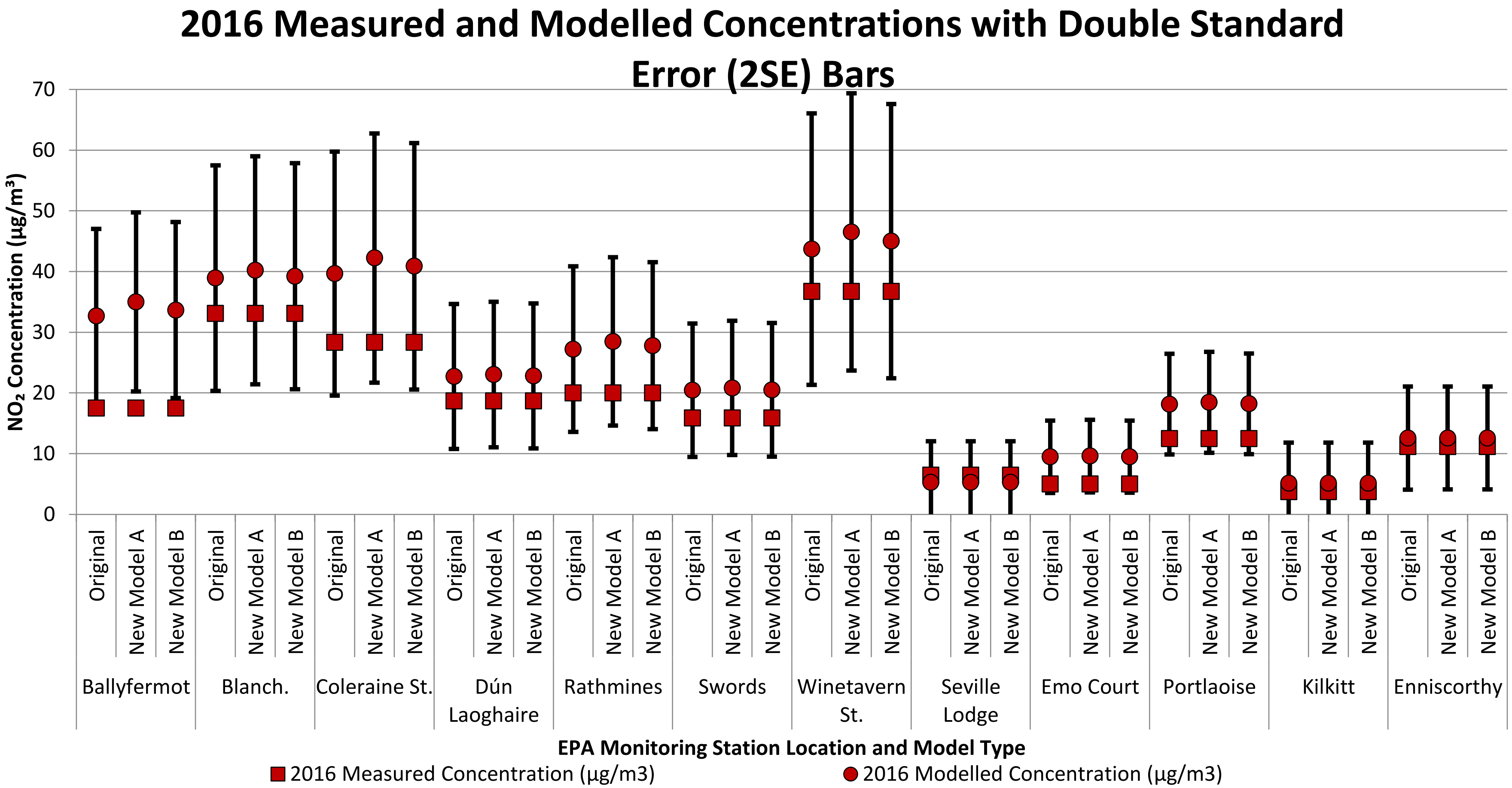


Figure 5.6: 2016 Measured and Modelled NO_2 Concentrations with Double Standard Error (2SE) High-Low Bars

Annual average NO_2 concentrations measured at each of the EPA monitoring stations were compared to the concentrations calculated using the original model methodology and the new model methodology. Table 5.7 below summarises the measured concentrations and the modelled concentrations at each of the sites. The differences between measured and modelled concentrations were between the range of –12.0 and +17.4 μg/m^3. The larger differences were experienced in urban/sub-urban environments whilst differences at rural locations (such as Kilkitt, Seville Lodge and Emo Court) were in the range of –1.2 and +4.6 μg/m^3. The anomalies in these results were locations where modelled results underestimated the NO_2 concentrations (St. John's Road and Ringsend) and as previously discussed this could be due to sources of NO_2 which are not covered by the variables in the model.

The concentrations for the Original Model methodology and New Model B methodology were consistently similar throughout. This reflects the fact that the differences between the models affect only one of the predictor variables (IDWVKT) and the emissions weightings have been calibrated to maintain consistency with the original model. The observed similarity in results confirms the ability of the new model method to retain the accuracy of the original model while introducing the potential to analyse the impact on concentrations of traffic variables and the vehicle fleet in more detail. The similarity of the Original and New Model B results in rural environments, such as Seville Lodge, Emo Court and Kilkitt, highlights that the vehicle fleets in these locations are similar to the national average. In contrast, a number of other locations, such as Coleraine Street, St. John's Road and Winetavern Street, produced higher concentrations within the New Models A and B compared to the Original Model due to the urban nature of the environments, where the percentage of vehicles (LPSVs and HDVs), which emit more NO_2 than the average vehicle, would be greater than the national average. The new model can be utilised to develop mitigation measures which target particular vehicle types, such as Euro Class restrictions on particular routes or migrating parts of the vehicle fleet to low emission vehicles. A range of mitigation strategies will be investigated using the model later in Chapter 6.

Table 5.7: Measured and Modelled NO_2 Concentrations at EPA Monitoring Station Locations (Locations and Measured Concentrations: Environmental Protection Agency, 2019)

Year / Monitoring Station	Measured Conc. (µg / m^3)	Original Model Conc. (µg / m^3)	New Model A Conc. (µg / m^3)	New Model B Conc. (µg / m^3)
2018 Seville Lodge, Kilkenny	5.9	4.987 ± 3.421	4.990 ± 3.421	4.987 ± 3.421
2017 Seville Lodge, Kilkenny	5.4	4.879 ± 3.436	4.880 ± 3.436	4.879 ± 3.436
2016 Seville Lodge, Kilkenny	6.4	5.282 ± 3.371	5.285 ± 3.371	5.283 ± 3.371
2018 Emo Court, Laois	5.5	9.159 ± 3.045	9.311 ± 3.058	9.165 ± 3.045
2017 Emo Court, Laois	4.2	9.291 ± 3.024	9.439 ± 3.037	9.308 ± 3.026
2016 Emo Court, Laois	5.0	9.467 ± 2.975	9.602 ± 2.987	9.498 ± 2.978
2018 Portlaoise, Laois	11.2	17.122 ± 3.929	17.379 ± 3.952	17.102 ± 3.928
2017 Portlaoise, Laois	11.1	16.435 ± 3.697	16.652 ± 3.716	16.427 ± 3.696
2016 Portlaoise, Laois	12.5	18.155 ± 4.139	18.446 ± 4.164	18.218 ± 4.144
2018 Dundalk, Louth	13.6	19.787 ± 5.012	19.967 ± 5.027	19.784 ± 5.012
2018 Kilkitt, Monaghan	3.4	4.850 ± 3.395	4.833 ± 3.393	4.837 ± 3.394
2017 Kilkitt, Monaghan	2.9	4.943 ± 3.379	4.925 ± 3.377	4.928 ± 3.377
2016 Kilkitt, Monaghan	3.7	5.129 ± 3.345	5.112 ± 3.343	5.115 ± 3.344
2016 Enniscorthy, Wexford	11.2	12.566 ± 4.242	12.572 ± 4.242	12.570 ± 4.242
2018 Ballyfermot, Dublin	17.5	31.875 ± 7.043	34.111 ± 7.237	32.493 ± 7.097
2017 Ballyfermot, Dublin	16.6	33.736 ± 7.565	36.227 ± 7.781	34.568 ± 7.637
2016 Ballyfermot, Dublin	17.5	32.685 ± 7.165	34.993 ± 7.365	33.656 ± 7.250
2018 Blanchardstown, Dublin	31.8	39.034 ± 9.290	40.369 ± 9.406	39.076 ± 9.294
2017 Blanchardstown, Dublin	26.8	37.955 ± 9.364	39.007 ± 9.456	38.025 ± 9.370
2016 Blanchardstown, Dublin	33.1	38.917 ± 9.292	40.205 ± 9.404	39.223 ± 9.319
2017 Coleraine Street, Dublin	26.7	38.056 ± 9.757	40.484 ± 9.968	39.035 ± 9.842
2016 Coleraine Street, Dublin	28.3	39.653 ± 10.043	42.239 ± 10.268	40.878 ± 10.150
2018 Davitt Road, Dublin	25.7	32.689 ± 7.304	34.910 ± 7.497	33.311 ± 7.358
2018 Dún Laoghaire, Dublin	19.1	22.347 ± 5.903	22.661 ± 5.930	22.375 ± 5.905
2017 Dún Laoghaire, Dublin	17.9	21.966 ± 5.769	22.356 ± 5.803	22.039 ± 5.775
2016 Dún Laoghaire, Dublin	18.7	22.704 ± 5.964	23.046 ± 5.994	22.808 ± 5.973
2018 Rathmines, Dublin	21.1	27.073 ± 6.808	28.328 ± 6.918	27.469 ± 6.843
2017 Rathmines, Dublin	17.1	26.342 ± 6.825	27.566 ± 6.931	26.824 ± 6.866
2016 Rathmines, Dublin	20.0	27.200 ± 6.820	28.480 ± 6.931	27.789 ± 6.871
2018 Ringsend, Dublin	27.2	20.950 ± 4.891	22.448 ± 5.021	21.370 ± 4.927
2017 Ringsend, Dublin	22.3	21.501 ± 4.990	23.314 ± 5.147	22.143 ± 5.045
2018 St. John's Road, Dublin	44.5	29.743 ± 6.630	32.583 ± 6.876	30.657 ± 6.709
2018 Swords, Dublin	16.5	21.975 ± 5.737	22.436 ± 5.777	21.963 ± 5.736

Year / Monitoring Station	Measured Conc. (µg / m^3)	Original Model Conc. (µg / m^3)	New Model A Conc. (µg / m^3)	New Model B Conc. (µg / m^3)
2017 Swords, Dublin	14.1	19.059 ± 5.273	19.462 ± 5.308	19.088 ± 5.276
2016 Swords, Dublin	15.9	20.426 ± 5.496	20.828 ± 5.531	20.507 ± 5.503
2018 Winetavern Street, Dublin	29.0	43.681 ± 11.181	46.542 ± 11.429	44.612 ± 11.262
2017 Winetavern Street, Dublin	27.2	43.304 ± 11.299	45.891 ± 11.523	44.305 ± 11.386
2016 Winetavern Street, Dublin	36.7	43.679 ± 11.183	46.523 ± 11.429	44.998 ± 11.297

The original study captured 78% of the spatial variability in NO_2 with a cross validation R^2 of 77.4% (Naughton et al., 2018). The cross validation R^2 was similar when analysing the 2016 to 2018 measurements against the Original Model methodology at 75.44%, whilst the New Model A and New Model B methodologies were also similar to the original study at 76.08% and 75.58% respectively, as shown in Figure 5.7, Figure 5.8 and Figure 5.9. These cross validation R^2 values are in the upper range of results achieved in other LUR models across Europe, which had cross validation R^2 between 55% and 92% (Beelen et al., 2013) and align with the accuracy of advanced air dispersion models which achieved cross validation R^2 between 4% and 83% for NO_2 (Briggs, 2005; Benson, 1992; Karppinen et al., 2000; Kukkonen et al., 2001) and have significantly greater data requirements and computation power to achieve accurate air pollution estimates. The St. John's Road location had a significant impact on the R^2 values of all model methodologies as the modelled concentration underestimated by 11 – 14 µg/m^3 across all model methodologies. It is likely that other factors which are not accounted for in the model predictor variables are contributing to NO_2 concentrations at this site such as train traffic entering and leaving Heuston Station, areas where engine idling is common such as taxi ranks / bus stops and traffic queuing or low traffic speeds at the traffic signalised junction / crossing. The cross-validation R^2 values increased significantly to approximately 86% for all model methodologies when accounting for all locations except St. John's Road.

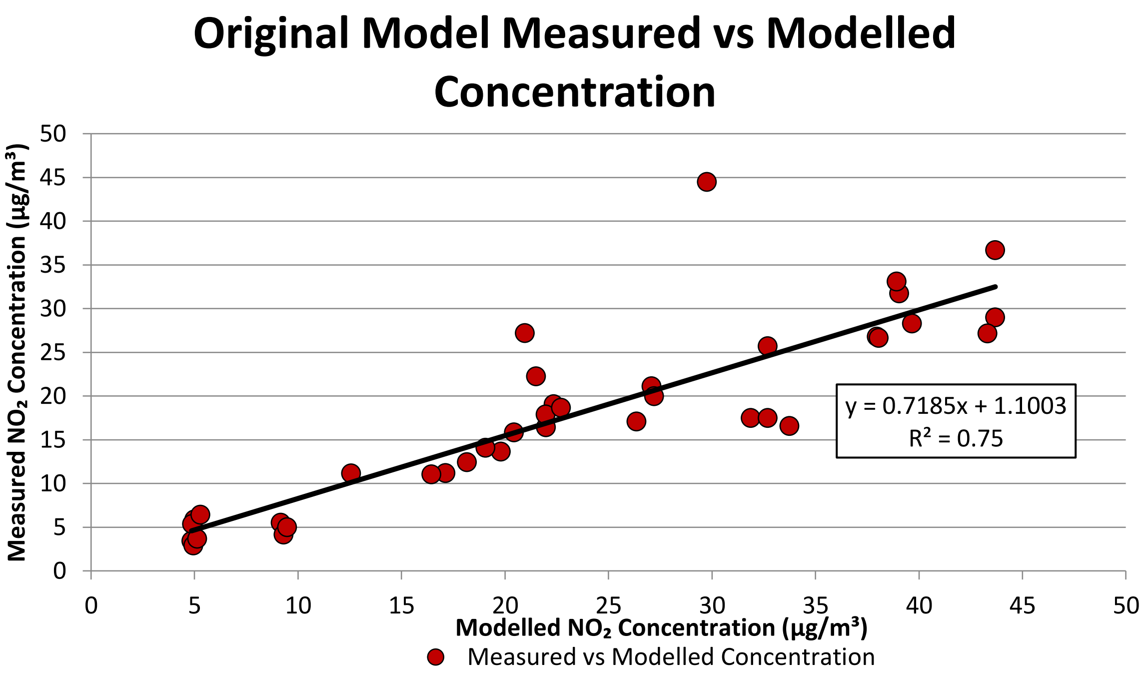


Figure 5.7: Measured vs Modelled NO_2 Concentrations – Original Model Methodology

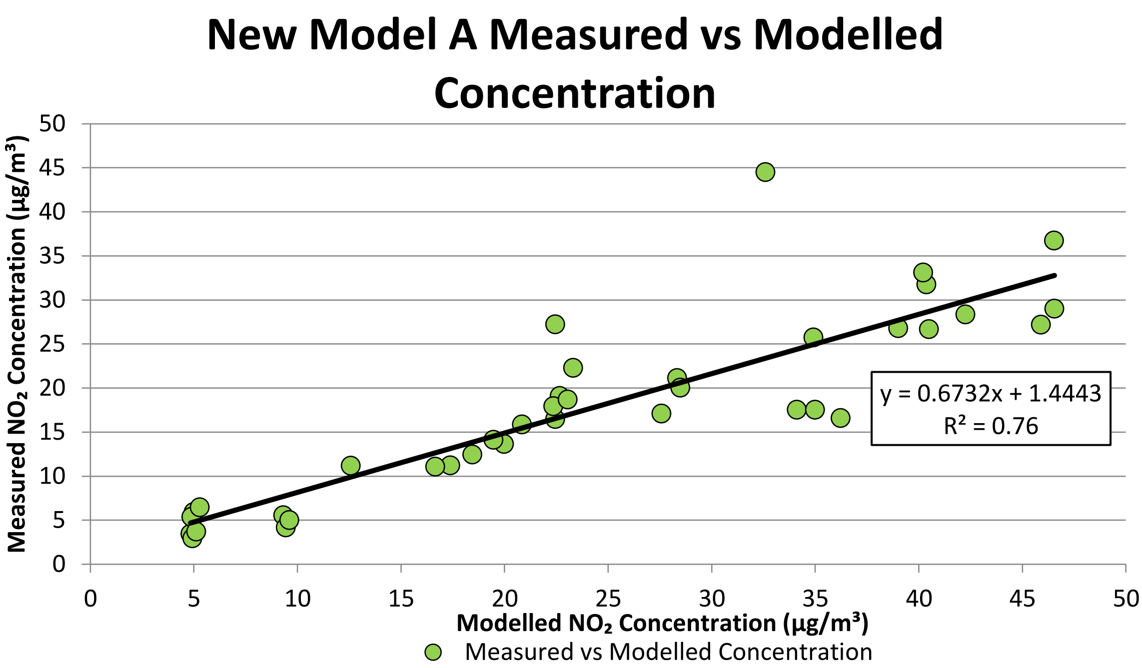


Figure 5.8: Measured vs Modelled NO_2 Concentrations – New Model A Methodology

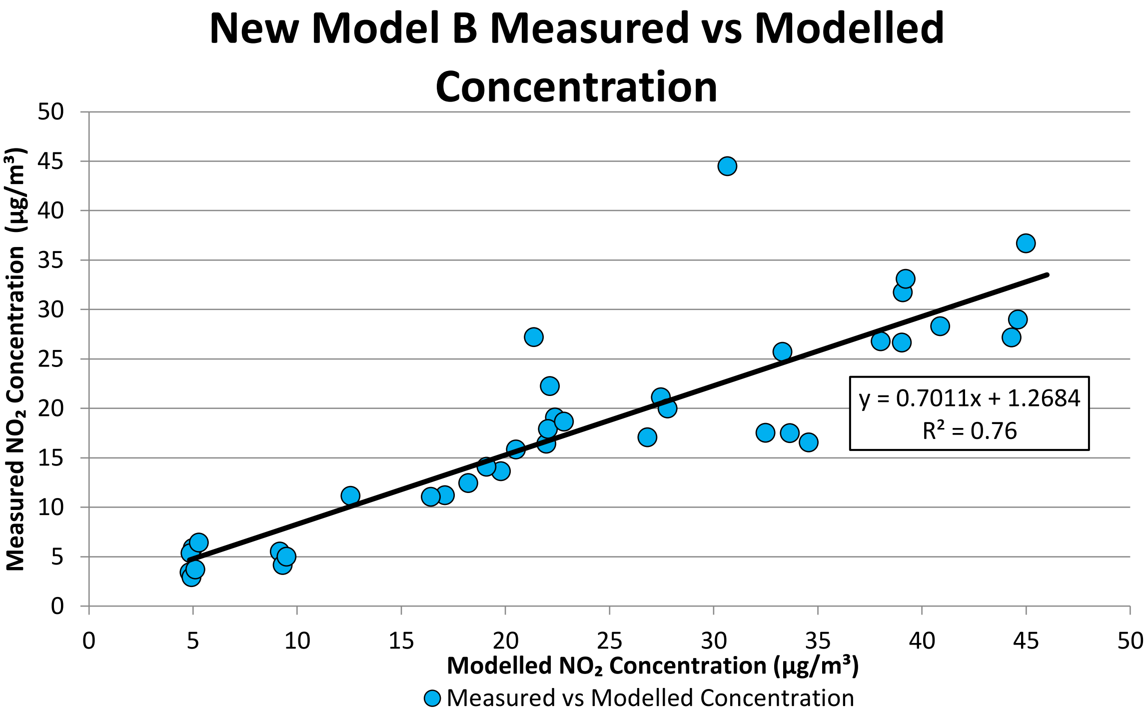


Figure 5.9: Measured vs Modelled NO_2 Concentrations – New Model B Methodology

5.1.4. Model Validation Study (Pre-Set Years (2016 to 2018)) Conclusion

The model validation study presented in this section demonstrates that the accuracy of the original model has been retained despite the significant period of time that has passed since it was first developed. Changes across the majority of predictor variables would have occurred over this period, in particular the traffic related variables. Sections 3.3.5 and 5.1.1 identified significant changes in the vehicle fleet breakdown between the original study period (2010 to 2012) and this study period (2016 to 2018) and, despite these changes, the accuracy of the model was largely unaffected. The inclusion of the NO_2 emission weightings for vehicle types within the IDWVKT variable did not negatively impact the accuracy of the model. An opportunity is therefore provided to examine mitigation measures linked to vehicle fleet breakdown and the effects of these changes on NO_2 concentrations. The updated WS-LUR model (New Model B methodology) was used to determine the performance of the model when presented with a unique scenario / environment such as the COVID lockdown period and the conclusions from this analysis are presented in Sections 5.2 and 5.3.

5.2. Unique Scenario / Environment (COVID Lockdown) Analysis Methodology and Data

This section contains details of the methodology and sources of data for each of the variables within the WS-LUR model (IDWVKT, commercial properties, meteorological, vehicle fleet breakdown, road density and natural/agricultural land use) for an analysis of the 1st COVID lockdown period (28th March 2020 to 17th May 2020). This analysis utilised the New Model B methodology developed within Chapters 3 and 4 to determine the accuracy of the model to estimate NO_2 concentrations under unique conditions and reinforce confidence in the use of the model in any scenario.

5.2.1. Inverse Distance Weighted Vehicle Kilometres Travelled Data

Major routes throughout the country experienced substantial changes in traffic flows during the 1st COVID lockdown period (between 28th March 2020 and 17th May 2020) with reduced flows for all vehicle types and AADT throughout the country due to the introduction of travel restrictions during this period (Transport Infrastructure Ireland, 2022). The restrictions on travel to a maximum of 2km from a person’s household combined with closure of all non-essential businesses removed the need to travel for leisure or work, while all trips for essential shopping such as groceries were localised to the nearest towns and villages. This had a considerable impact on traffic flows on major routes with less need for intercity travel.

Traffic flow data for the pre-COVID scenario was based on outputs from the National Transport Authority’s East Region Model (National Transport Authority, 2020) which contains routes of all standards (motorway, national, rural, local, unclassified routes) within the Leinster province and represented 2018 conditions. Traffic flow data for the COVID scenario was obtained from the Transport Infrastructure Ireland website (Transport Infrastructure Ireland, 2022) which provided measured traffic flows on motorway and national routes. Flows for rural, local and unclassified routes were not available for the COVID lockdown period and therefore were excluded from the unique COVID scenario analysis as substituting flows from the same period in previous years would not be accurate due to the unique traffic conditions that existed during the lockdown period when flows were much lower than normal. Hence, the WS-LUR model was employed to calculate the expected changes in concentrations due to a combination of the measured changes in major route flows experienced during COVID and the exclusion of traffic on minor routes. To investigate the potential confounding within the results, the effect of the exclusion of the rural, local and unclassified route flows on modelled concentrations was also quantified separately, as described in Section 5.3.3.

The AADT flow reductions were in the range of 30% to 75% on the majority of routes in the country with reductions of greater than 75% along short sections of a number of routes, as shown in Figure 5.10. A number of sections of routes showed increases of greater than 50% across all vehicle types, mainly on the west coast; these are attributable to the lack of counter data on these sections which resulted in interpolation errors due to the significant distances from the nearest traffic counters. The interpolation errors did not impact the analysis as the affected sections of routes were located on the west coast of Ireland and the EPA monitoring stations considered in this analysis were located in the Leinster province and are identified in Table 5.8. Therefore, the affected routes were located more than 5km from the study locations, which is the maximum distance from a study location considered for all the variables within the WS-LUR model. Reductions of greater than 75% in car / taxi flows were experienced on longer sections of routes in comparison to the AADT flows, as shown in Figure 5.11. This would have been expected as cars are predominantly privately owned and both the cars and taxis were not scheduled transport modes. The closure of all non-essential businesses and restrictions on all non-essential travel reduced the need for cars and taxis to travel along these routes. The reduction in LGV flows was mainly in the 30% to 75% range and was not as large as the car flow reductions, as shown in Figure 5.12. A key difference in the LGV fleet in comparison to the cars fleet was the ownership type, where a larger proportion of the fleet were business-owned vehicles and more of these LGVs which could be used for services such as deliveries, continued to operate during the lockdown period.

The reductions experienced in the HGV flows were in the range of 0 to 30% for the majority of the routes and this was the vehicle type least affected by the lockdown restrictions, as shown in Figure 5.13. This was expected as HGVs were the main transport mode used for large scale deliveries to businesses such as groceries, agriculture and logistics which were operating as essential services during the lockdown period.

The publicly owned services within the cities and local routes operated at 80% capacity during the first lockdown period, but inter-city services were suspended by the majority of publicly funded and private bus companies (National Transport Authority, 2020; National Transport Authority, 2020; National Transport Authority, 2020). This resulted in larger reductions of greater than 30% on the major intercity routes with smaller reductions in the range of 0 to 30% in areas around cities, towns and villages which were operating near full capacity during the lockdown period, as shown in Figure 5.14. Similar to the car fleet, the motorcycle fleet is predominantly privately owned and the flow reductions experienced during lockdown were greater than 30% for the majority of routes, as shown in Figure 5.15.

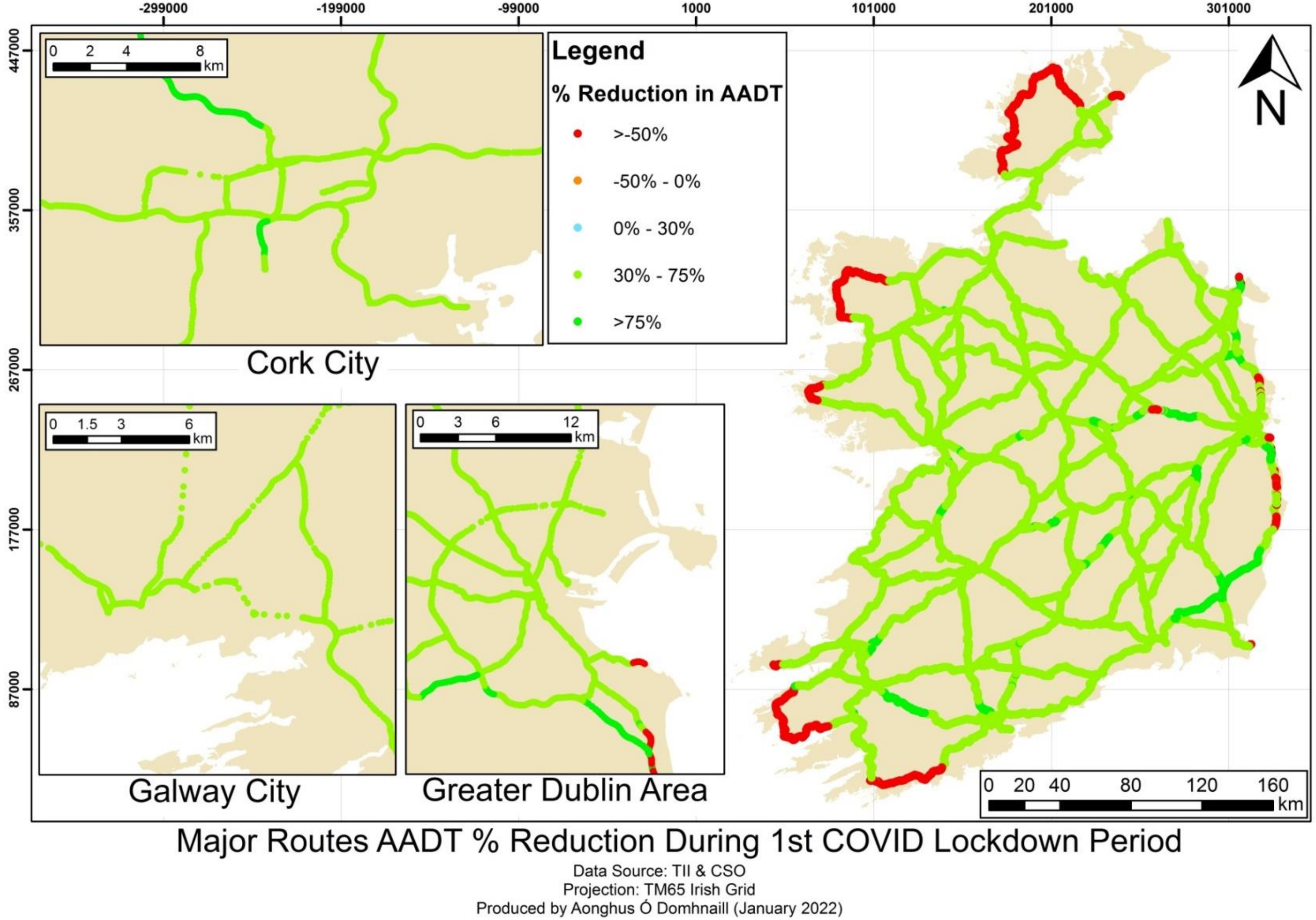


Figure 5.10: Major Routes AADT % Reduction During 1st COVID Lockdown Period

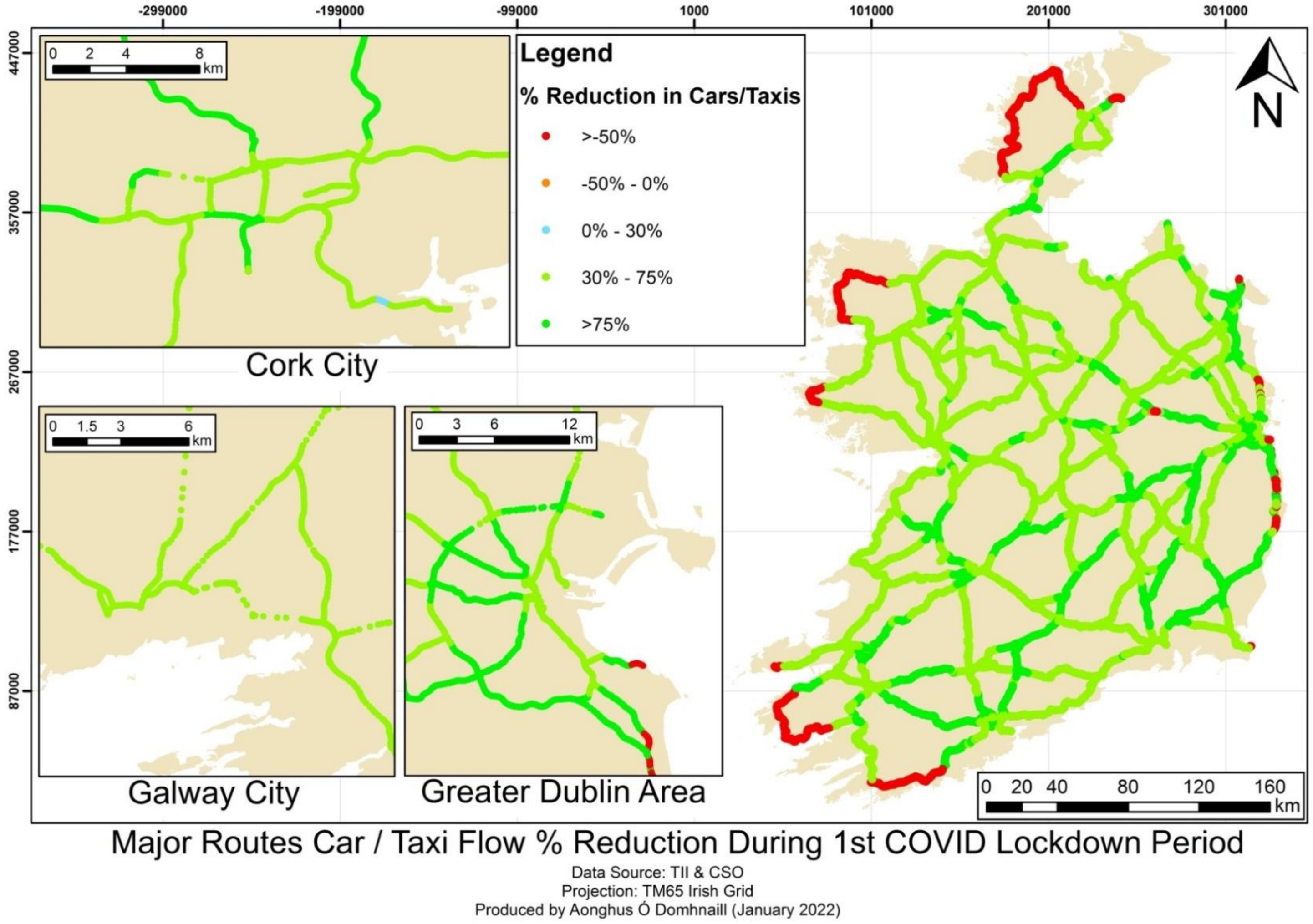


Figure 5.11: Major Routes Car / Taxi Flow % Reduction During 1st COVID Lockdown Period

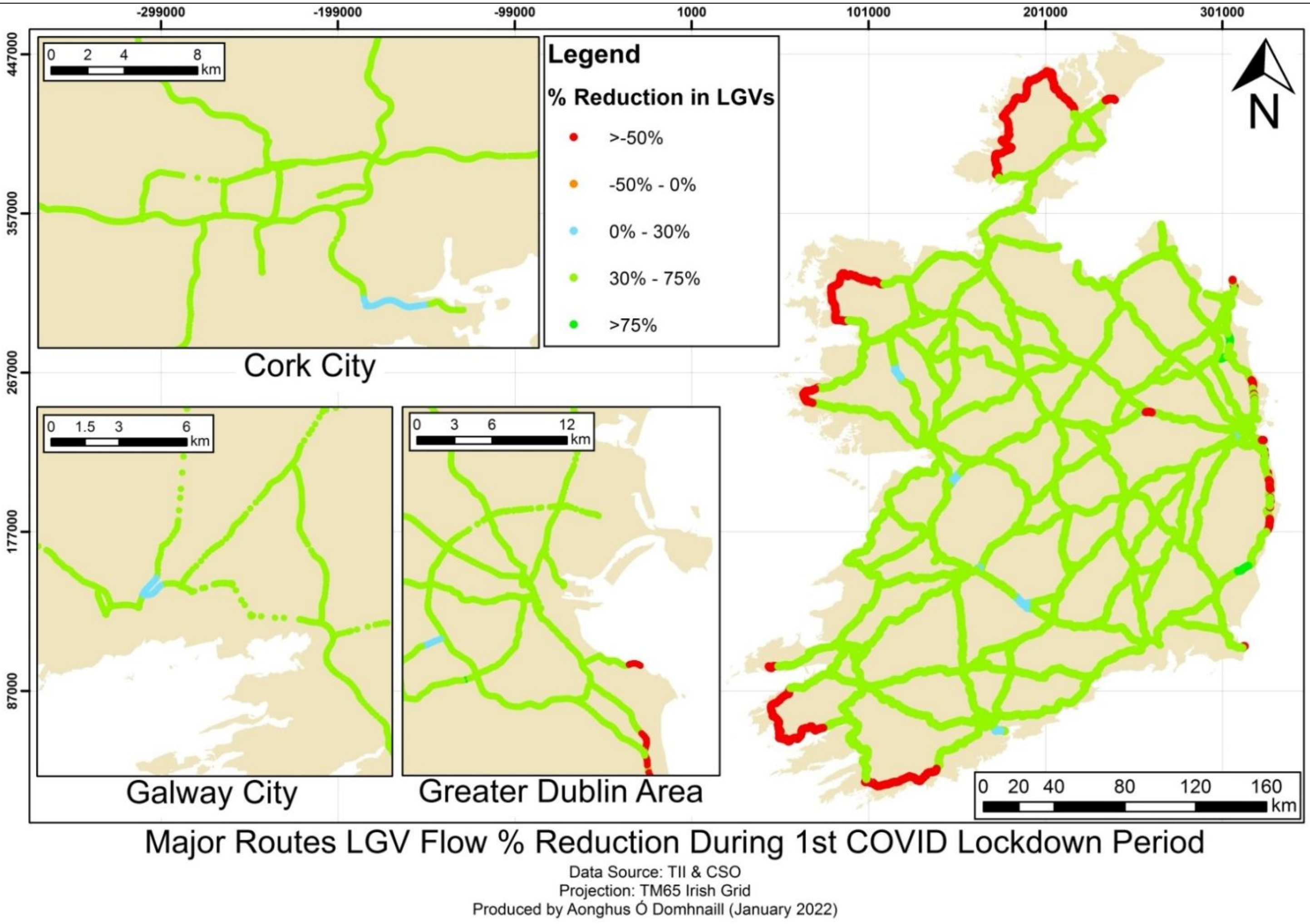


Figure 5.12: Major Routes LGV Flow % Reduction During 1st COVID Lockdown Period

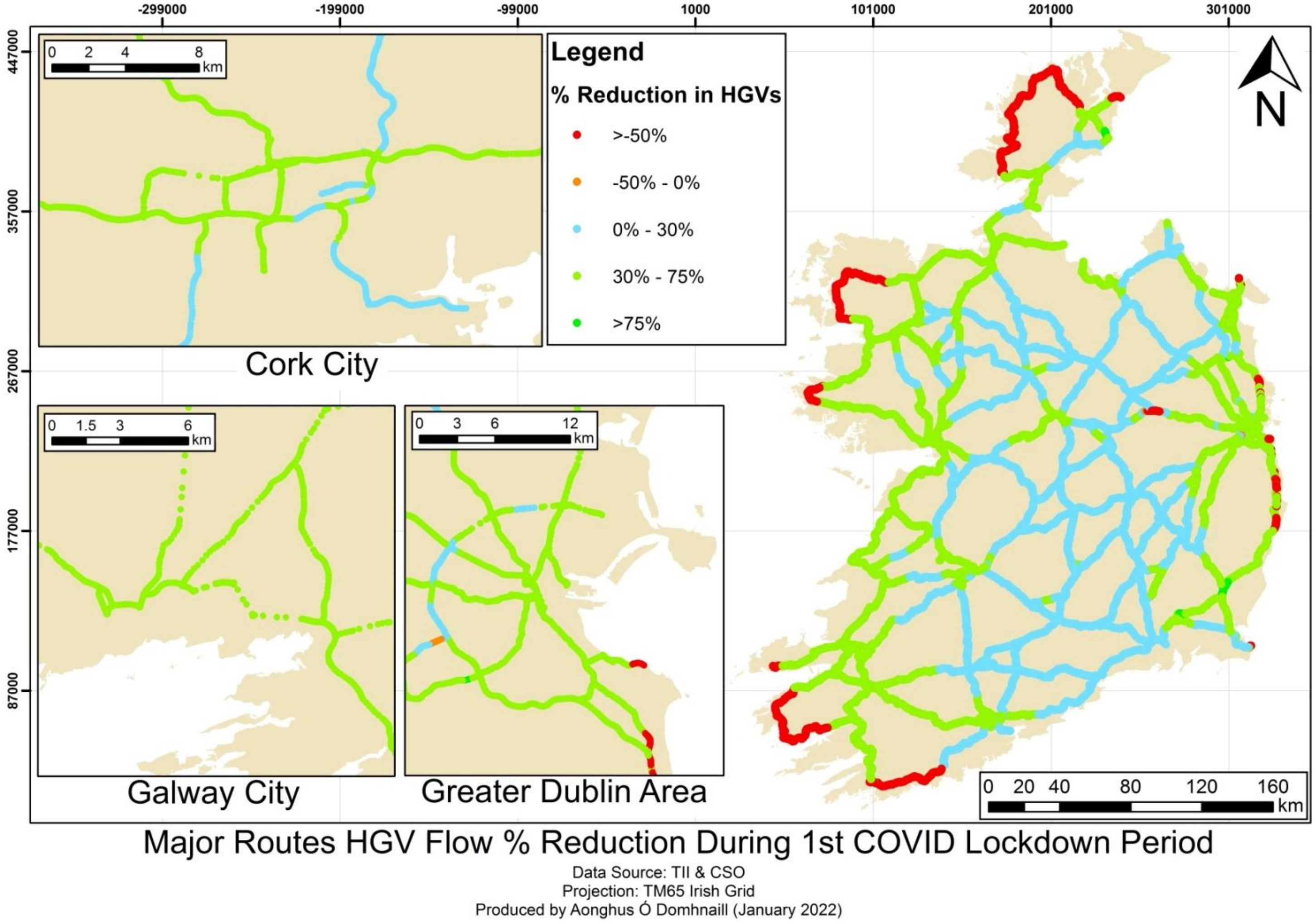


Figure 5.13: Major Routes HGV Flow % Reduction During 1st COVID Lockdown Period

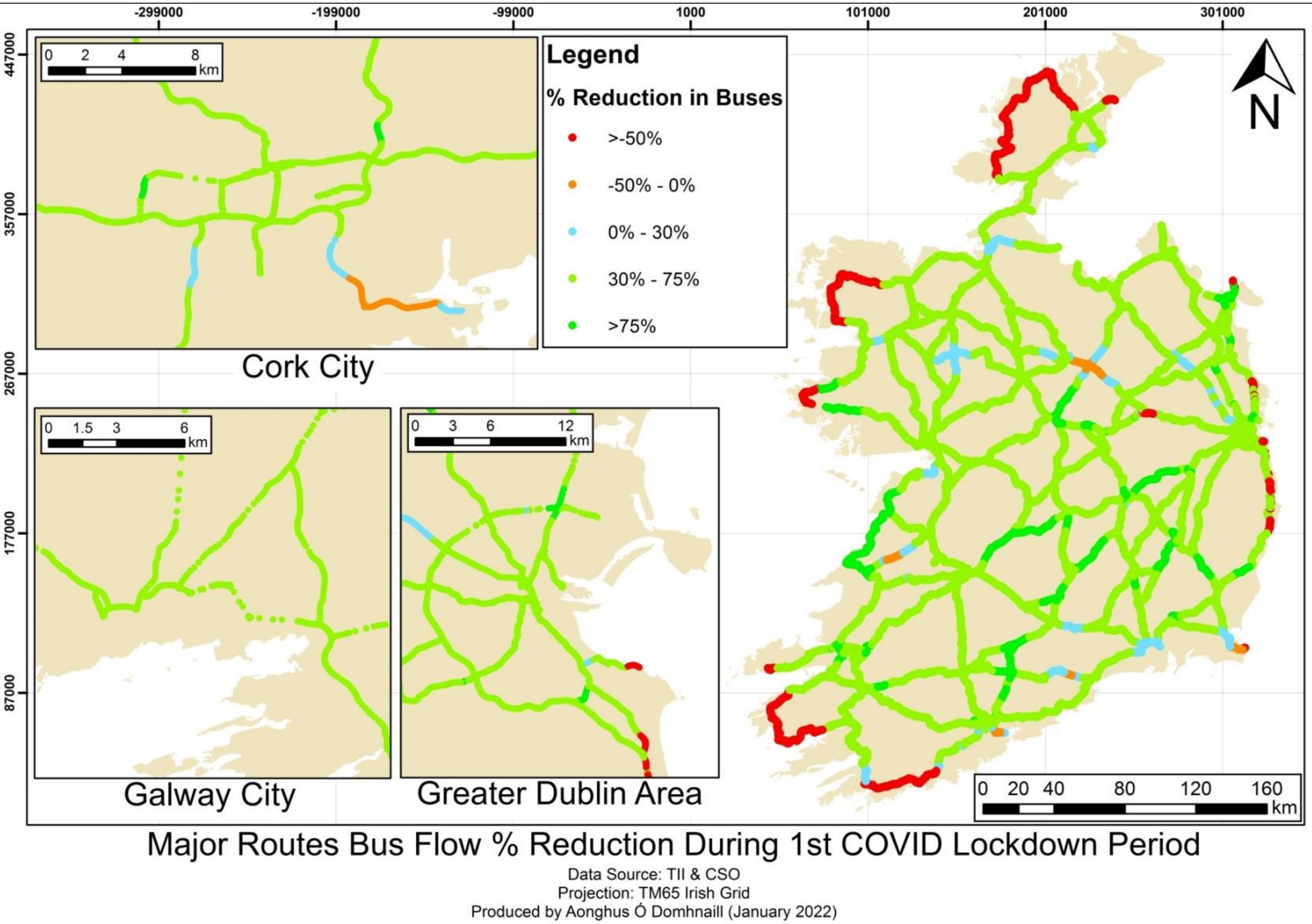


Figure 5.14: Major Routes Bus Flow % Reduction During 1st COVID Lockdown Period

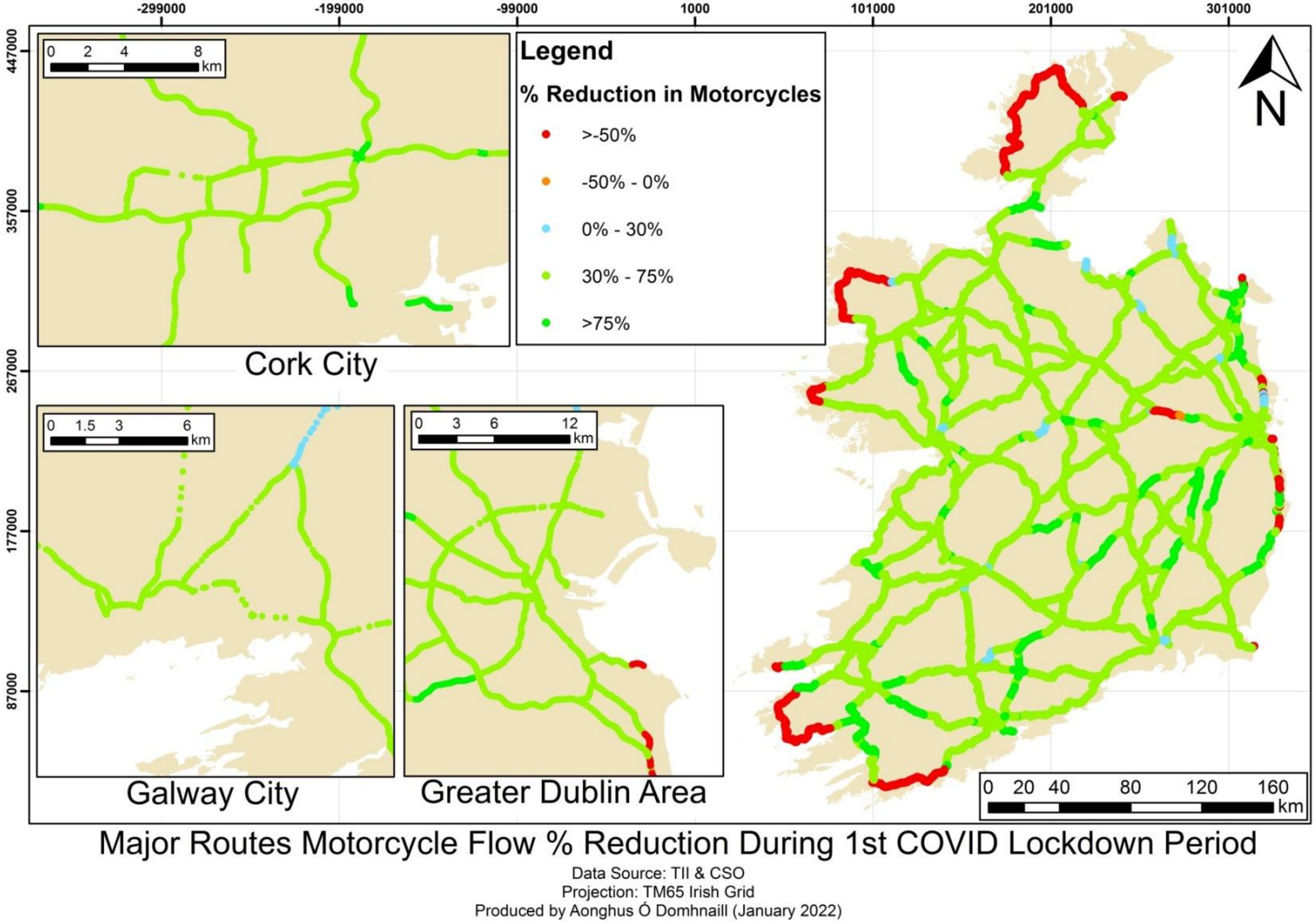


Figure 5.15: Major Routes Motorcycle Flow % Reduction During 1st COVID Lockdown Period

Table 5.8 presents the computed IDWVKT data for all directional sectors at each EPA air quality monitoring station for both the pre-COVID and COVID scenarios. In the majority of cases, the IDWVKT reduced considerably due to the restrictions on traffic during the lockdown period but also due to the exclusion of the minor route flows from the COVID scenario. The exclusion of minor route flows resulted in the IDWVKT variable being reduced to zero in one directional sector for six monitoring stations (Ballyfermot, Blanchardstown, Pearse Street, Rathmines, St. John's Road and Winetavern Street). These reductions were in the range of 77 790 and 196 574. Multiple directional sectors were reduced to zero due to the exclusion of the minor routes at three monitoring stations (Dún Laoghaire, Ringsend and Swords). The reductions in IDWVKT within individual directional sectors at these stations were in the range of 8 623 and 115 356. In a small number of cases, the variable values increased slightly and a number of reasons were identified such as (i) an increase in the number of heavier polluting vehicles which offset the reduction in passenger cars, (ii) the majority of routes surrounding a study location being major routes and therefore the exclusion of the minor routes had a minimal effect or (iii) the traffic flow data being obtained from different sources for the two scenarios.

The shapefiles for the TII and NTA data varied in a number of locations. The TII shapefile was constructed using polylines, which accurately matched the horizontal alignment of the routes throughout whilst the NTA shapefile was constructed using lines which matched the routes at the start and end points but slightly skewed from the actual alignment in between the points. This was carried out to reduce the size of the shapefile considerably, assisting with processing time. The errors for the majority of routes were minimal due to the short lengths of the links but in a small number of cases, particularly in rural areas and on the boundary of the network, the horizontal curvature of the routes changed considerably and the distance between the route and study location was different, which affected the inverse distance weighting of the variable. The EPA air quality monitoring stations selected for this analysis were located within the Greater Dublin Area; mainly an urban / sub-urban environment where the links were shorter and therefore the difference in alignment of the links in the TII and NTA shapefiles were minimal.

Table 5.8: Inverse Distance Weighted Vehicle Kilometres Travelled by Directional Sector for Pre-COVID and COVID Scenarios

INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED									
EPA Monitoring Station	**Scenario**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot, Dublin	Pre-COVID	194 768	161 553	188 732	145 847	263 197	216 931	416 008	306 598
	COVID	211 906	120 917	77 079	0*	67 004	104 332	59 585	192 667
Blanchardstown, Dublin	Pre-COVID	77 790	236 696	439 530	345 875	396 828	208 504	97 705	482 825
	COVID	0*	197 784	140 947	511 994	463 994	185 194	148 332	325 415
Dún Laoghaire, Dublin	Pre-COVID	16 682	5 914	8 623	9 422	116 102	174 304	116 111	60 485
	COVID	0*	0*	0*	0*	20 156	48 983	15 486	19 508
Pearse Street, Dublin	Pre-COVID	285 306	217 652	124 010	160 562	212 096	203 181	267 116	314 616
	COVID	38 960	14 455	0*	13 031	31 707	63 137	149 514	133 689
Rathmines, Dublin	Pre-COVID	285 126	194 927	155 137	136 245	114 889	143 960	132 718	174 800
	COVID	104 799	35 250	17 767	6 851	0*	63 308	23 668	85 704
Ringsend, Dublin	Pre-COVID	115 356	18 791	11 825	19 563	163 191	167 176	255 054	232 397
	COVID	0*	0*	0*	2 337	17 581	16 767	80 034	74 334
St. John’s Road, Dublin	Pre-COVID	140 106	398 692	372 956	185 819	155 607	164 858	421 177	102 699
	COVID	596 927	632 082	159 130	33 206	21 248	0*	256 989	46 193
Swords, Dublin	Pre-COVID	11 444	120 126	55 381	286 570	259 513	52 740	22 701	54 117
	COVID	28 672	49 795	29 015	51 921	52 501	0*	0*	0*
Winetavern Street, Dublin	Pre-COVID	221 971	334 984	207 967	242 724	237 848	196 574	261 188	219 727
	COVID	151 832	130 865	90 678	62 785	96 267	0*	115 896	110 341

* No traffic flow data within directional sector when considering only major routes

5.2.2. Commercial Properties Data

Commercial properties data was retrieved from the EPA GIS Department and An Post / Geodirectory (GeoDirectory, 2020) in ArcGIS points file format. This data was used to determine the number of commercial properties surrounding study locations and respresented records of all commercial properties in Ireland as of Summer 2020, which included details such as location and business type. Due to the lockdown introduced by the Irish Government on the 28th March 2020 a large proportion of commercial properties were closed until lockdown restrictions were eased unless they were categorised as essential businesses / services (IBEC, 2020; Department of the Taoiseach, 2020). A list published by the government identified businesses / services across a number of sectors such as agriculture, manufacturing, construction, trade (wholesale and retail), health, etc. as essential and these therefore remained operational during the lockdown period. Hence, the commercial properties data in the WS-LUR model were modified to include only essential businesses / services as formally defined by the Irish Government during the first lockdown period.

Table 5.9 presents the number of commercial properties surrounding each EPA monitoring station in a pre-COVID scenario, which represents a time when lockdown restrictions were not in place and all commercial properties were operational, and a COVID scenario, which represents the lockdown period when only essential businesses were operational. The largest reductions in operational commercial property numbers occurred around city centre based monitoring stations such as Pearse Street and Winetavern Street, which are business district areas where the majority of commercial properties were non-essential retail, entertainment or non-essential businesses where remote working was implemented. The difference in commercial property numbers between pre-COVID and COVID scenarios was minor around rural monitoring stations such as Emo Court and Kilkitt, where businesses were mainly in essential categories such as agriculture, construction or essential retail.

Figure 5.16 illustrates the operational commercial properties comparison for the pre-COVID and COVID scenarios around the Trinity College Dublin campus. The number of commercial properties within each of the 1km radius wind directional sectors represented the value for the commercial properties predictor variable within the enhanced WS-LUR model equation.

Table 5.9: Commercial Properties by Directional Sector for Pre-COVID and COVID Scenarios

NUMBER OF OPERATIONAL COMMERCIAL PROPERTIES									
EPA Monitoring Station	**Scenario**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot, Dublin	Pre-COVID	94	44	16	87	61	29	16	112
	COVID	13	8	4	20	19	4	2	25
Blanchardstown, Dublin	Pre-COVID	30	1	2	34	8	28	204	24
	COVID	3	1	1	3	7	8	51	9
Dún Laoghaire, Dublin	Pre-COVID	623	43	155	49	34	74	33	302
	COVID	70	8	31	16	9	5	4	54
Pearse Street, Dublin	Pre-COVID	869	687	871	706	1589	906	1765	1183
	COVID	67	29	43	85	186	91	110	96
Rathmines, Dublin	Pre-COVID	424	321	195	110	88	62	156	91
	COVID	26	43	40	16	20	11	22	14
Ringsend, Dublin	Pre-COVID	7	6	26	6	54	49	125	5
	COVID	4	2	12	2	8	12	23	2
St. John’s Road, Dublin	Pre-COVID	63	183	359	559	175	221	62	11
	COVID	12	26	30	45	21	25	3	4
Swords, Dublin	Pre-COVID	13	38	100	110	328	19	12	15
	COVID	3	12	13	21	65	3	4	0
Winetavern Street, Dublin	Pre-COVID	968	2090	2449	1351	674	1110	524	1254
	COVID	85	136	141	87	48	75	33	82
Emo Court, Laois	Pre-COVID	1	0	0	1	0	0	0	2
	COVID	1	0	0	1	0	0	0	1
Portlaoise, Laois	Pre-COVID	8	11	17	7	97	236	312	12
	COVID	2	4	12	2	11	45	37	1
Dundalk, Louth	Pre-COVID	63	72	118	60	14	63	654	352
	COVID	10	18	22	17	5	14	87	44
Kilkitt, Monaghan	Pre-COVID	5	2	3	1	1	1	0	1
	COVID	5	1	3	1	1	1	0	1

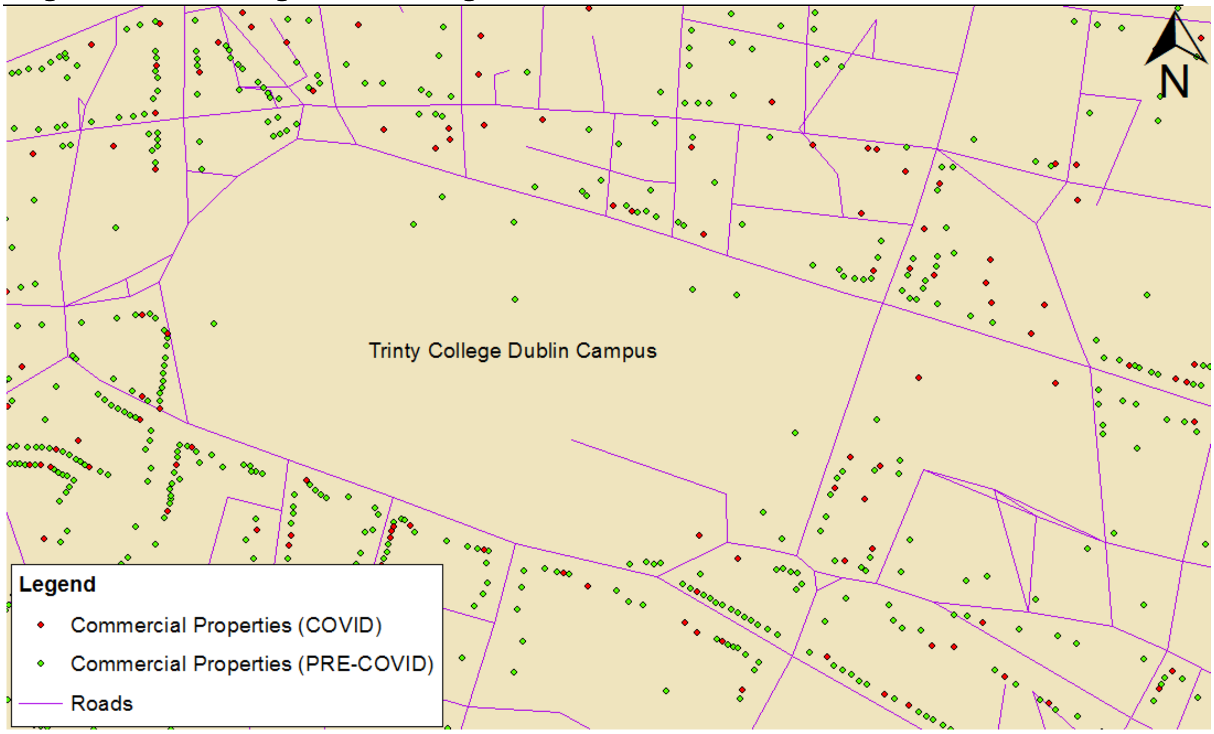


Figure 5.16: Commercial Properties around Trinity College Dublin Campus (Pre-COVID and COVID Scenarios)

5.2.3. Meteorological Data

Meteorological data for the first COVID lockdown period and a pre-COVID scenario was retrieved from the Met Éireann website (Met Éireann, 2020) for all meteorological monitoring stations, including all offshore stations, in Excel spreadsheet formats. These spreadsheets were used to determine the average wind speeds and the wind proportions within each of the directional sectors, which represented the values for the wind proportion factor and wind speed predictor variables within the enhanced WS-LUR model equation. Similar to the analysis described in Chapter 3, the locations of meteorological monitoring stations did not coincide with the EPA air quality monitoring stations, therefore, interpolation was required to estimate the meteorological variables (wind speeds, wind proportions, etc.) at each of the air quality stations. Equation 5.2 was used to calculate the variable values at all locations and utilised the inverse distance weighted approach to weight known points based on the distance to the study location.

$$f_0 = \left(1/_{d_1}\right) f_1 + \left(1/_{d_2}\right) f_2 + \cdots + \left(1/_{d_n}\right) f_n$$

Eqn. 5.2: Meteorological Factor Calculation at Study Location

Where:

n = Number of dependent points / triangulation accuracy ($n \leq 6$) (i.e. n = 0: study location; n = 1: closest known data point; n = 2: second closest known data point; …; n = 6: sixth closest known data point)

x_n = X co-ordinate of point n

y_n = Y co-ordinate of point n

d_n = Distance between study location and point n = $\sqrt{(x_0 - x_n)^2 + (y_0 - y_n)^2}$

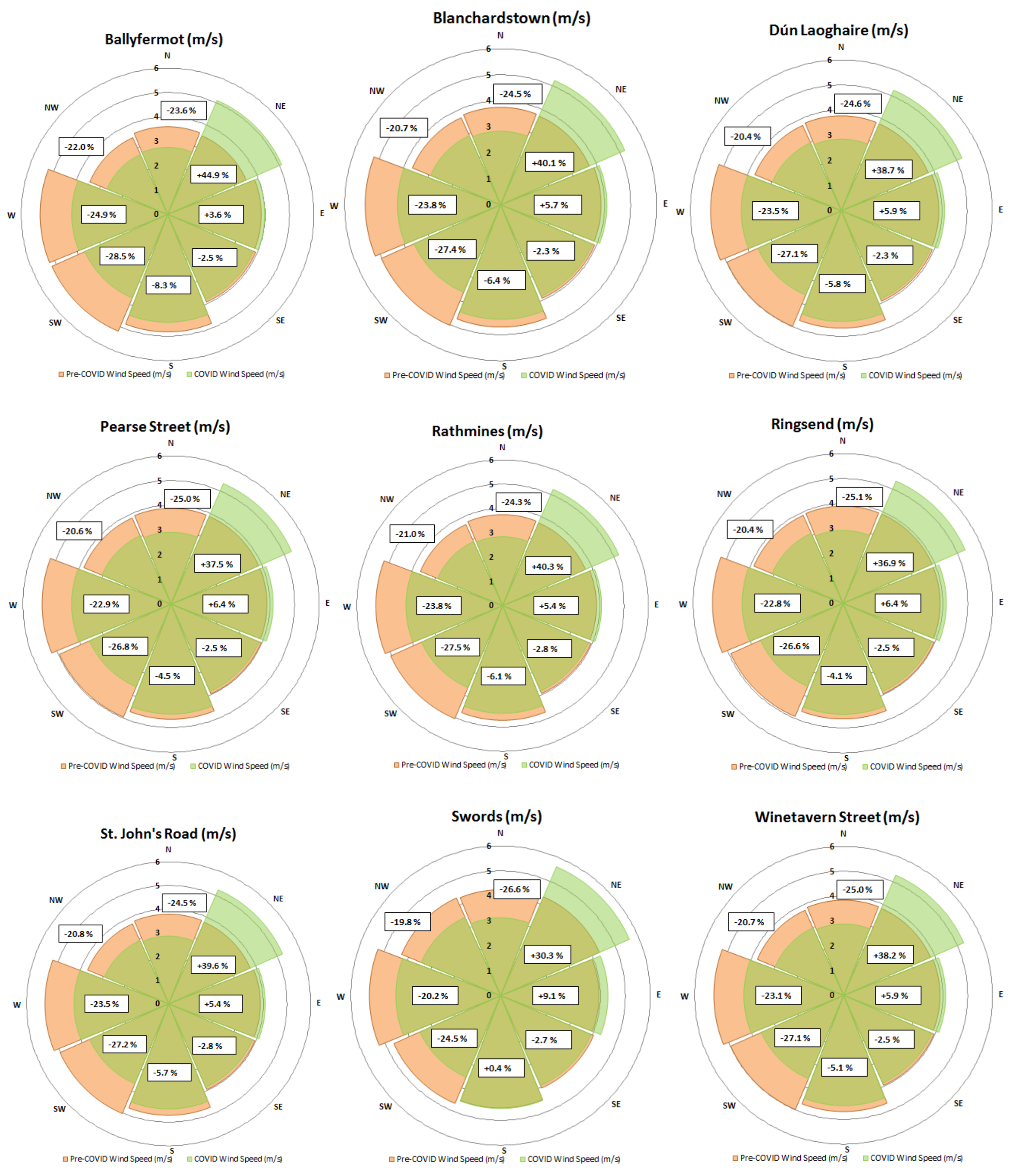
f_n = Meteorological variable value at point n (variables include wind speeds, wind direction proportions, etc.)

Table 5.10 shows the average wind speed by directional sector at each of the EPA monitoring station locations. The pre-COVID scenario was based on 2019 and represented a full year of data whilst the COVID scenario represented the period between the 28^{th} March and 17^{th} May 2020. The differences in average wind speeds are notable in the westerly directional sectors (southwest, west and northwest) and easterly directional sectors (northeast and east). Reductions in westerly average wind speeds were in the range of 10.8% and 28.5% across all stations. Increases in easterly average wind speeds varied with average wind speeds from the northeast increasing between 29.9% and 60.6% and average wind speeds from the east increasing between 1.7% and 11.1%. Changes in the southeast average wind speeds were minimal and ranged from -2.1% and -5.7%. The changes in north and south average wind speeds varied considerably based on the location. Stations located in east coast counties (Louth and Dublin) experienced considerable change (between -19.1% and -26.6%) in the north directional sector whilst there was minimal change in the south sector (between +0.4% and -8.3%). Inversely, stations located in the midlands (Emo Court, Portlaoise and Kilkitt) experienced minimal change in the north sector (between -6.1% and -7.8%) and considerable change (between -14.3% and -16.2%) in the south sector.

Table 5.10: Wind Speed by Directional Sector for Pre-COVID and COVID Scenarios

		WIND SPEED (m/s)							
EPA Station	**Scen.**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	Pre-C	3.60	3.52	3.84	3.93	4.82	5.20	5.23	3.46
	COV	2.75	5.10	3.98	3.83	4.42	3.72	3.93	2.70
		-23.6%	+44.9%	+3.6%	-2.5%	-8.3%	-28.5%	-24.9%	-22.0%
Blanchardstown	Pre-C	3.75	3.72	3.86	3.93	4.70	5.03	5.21	3.68
	COV	2.83	5.21	4.08	3.84	4.40	3.65	3.97	2.92
		-24.5%	+40.1%	+5.7%	-2.3%	-6.4%	-27.4%	-23.8%	-20.7%
Dún Laoghaire	Pre-C	3.78	3.77	3.87	3.93	4.67	4.99	5.20	3.73
	COV	2.85	5.23	4.10	3.84	4.40	3.64	3.98	2.97
		-24.6%	+38.7%	+5.9%	-2.3%	-5.8%	-27.1%	-23.5%	-20.4%
Pearse Street	Pre-C	3.88	3.87	3.88	3.97	4.66	4.96	5.23	3.83
	COV	2.91	5.32	4.13	3.87	4.45	3.63	4.03	3.04
		-25.0%	+37.5%	+6.4%	-2.5%	-4.5%	-26.8%	-22.9%	-20.6%
Rathmines	Pre-C	3.75	3.72	3.86	3.95	4.72	5.05	5.22	3.67
	COV	2.84	5.22	4.07	3.84	4.43	3.66	3.98	2.90
		-24.3%	+40.3%	+5.4%	-2.8%	-6.1%	-27.5%	-23.8%	-21.0%
Ringsend	Pre-C	3.90	3.90	3.89	3.97	4.64	4.93	5.23	3.87
	COV	2.92	5.34	4.14	3.87	4.45	3.62	4.04	3.08
		-25.1%	+36.9%	+6.4%	-2.5%	-4.1%	-26.6%	-22.8%	-20.4%
St. John’s Road	Pre-C	3.79	3.76	3.87	3.96	4.71	5.03	5.23	3.71
	COV	2.86	5.25	4.08	3.85	4.44	3.66	4.00	2.94
		-24.5%	+39.6%	+5.4%	-2.8%	-5.7%	-27.2%	-23.5%	-20.8%
Swords	Pre-C	4.25	4.32	3.94	4.05	4.50	4.69	5.26	4.30
	COV	3.12	5.63	4.30	3.94	4.52	3.54	4.20	3.45
		-26.6%	+30.3%	+9.1%	-2.7%	+0.4%	-24.5%	-20.2%	-19.8%
Winetavern Street	Pre-C	3.84	3.82	3.88	3.96	4.68	4.99	5.23	3.77
	COV	2.88	5.28	4.11	3.86	4.44	3.64	4.02	2.99
		-25.0%	+38.2%	+5.9%	-2.5%	-5.1%	-27.1%	-23.1%	-20.7%
Emo Court	Pre-C	2.78	2.48	2.97	3.65	4.29	4.33	4.23	3.05
	COV	2.61	3.98	3.04	3.48	3.61	3.18	3.17	2.36
		-6.1%	+60.5%	+2.4%	-4.7%	-15.9%	-26.6%	-25.1%	-22.6%
Portlaoise	Pre-C	2.81	2.49	2.98	3.68	4.32	4.39	4.30	3.10
	COV	2.63	4.00	3.03	3.47	3.62	3.21	3.21	2.37
		-6.4%	+60.6%	+1.7%	-5.7%	-16.2%	-26.9%	-25.3%	-23.5%
Dundalk	Pre-C	3.41	3.45	3.41	3.53	4.12	4.38	4.16	3.53
	COV	2.76	4.48	3.79	3.40	3.78	3.42	3.20	3.00
		-19.1%	+29.9%	+11.1%	-3.7%	-8.3%	-21.9%	-23.1%	-15.0%

		WIND SPEED (m/s)							
EPA Station	**Scen.**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Kilkitt	Pre-C	2.69	2.71	2.92	3.27	3.91	3.98	3.16	2.77
	COV	2.48	3.57	3.24	3.20	3.35	3.21	2.42	2.47
		-7.8%	+31.7%	+11.0%	-2.1%	-14.3%	-19.3%	-23.4%	-10.8%



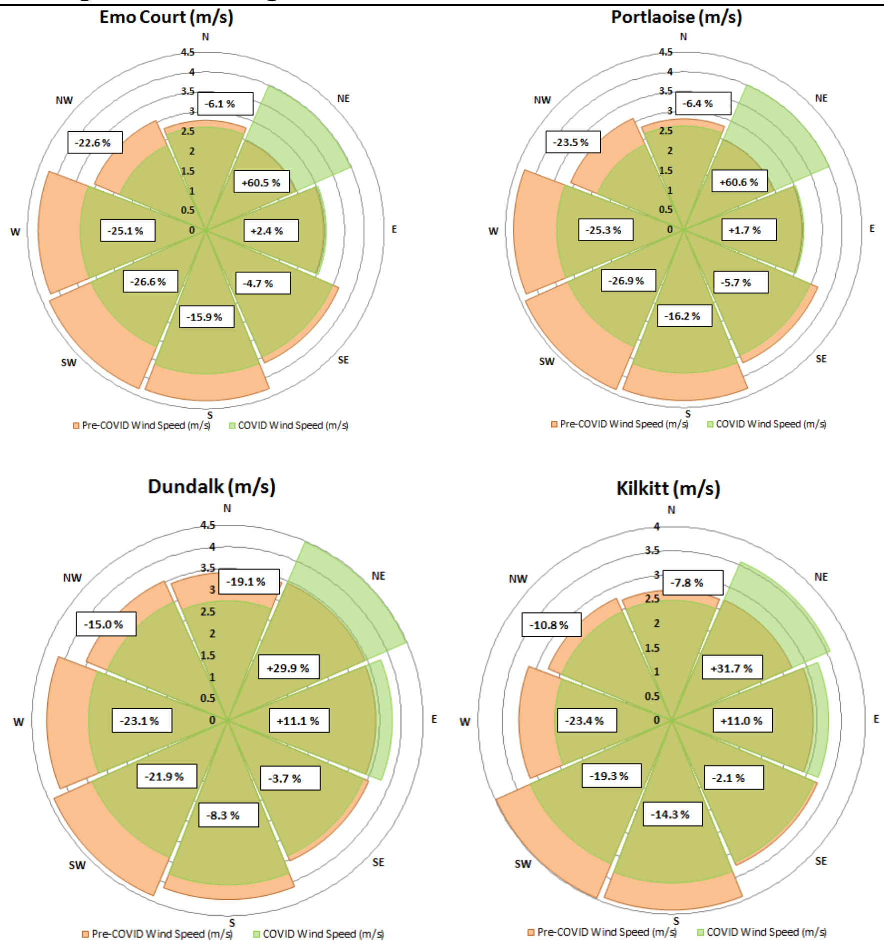


Figure 5.17: Wind Speed Roses Pre-COVID and COVID Scenarios

Table 5.11 shows the wind proportion by directional sector at each of the EPA monitoring stations for a pre-COVID scenario (full yearly data for 2019) and the first COVID lockdown period scenario. The changes in wind proportions between scenarios within the north, southeast, south and northwest sectors were minimal across all monitoring stations. In comparison to the pre-COVID scenario, the north proportions increased by approximately 2%, the southeast proportions decreased by approximately 3%, the south proportions decreased by approximately 6% and the northwest proportions increased by approximately 0.5%. However, the proportions in the northeast and east sectors increased by approximately 14% and 19% respectively during the COVID scenario, whilst the southwest and west proportions decreased by approximately 17% and 10% respectively in comparison to the pre-COVID scenario. These percentages represented the wind proportion factors within WS-LUR model equation and these changes in wind proportions would result in significant changes in the weightings of all the variables within these wind directional sectors. Therefore, the influence of variables within the northeast and east sectors on concentrations would increase and the influence of variables within the southwest and west sectors would reduce in the COVID scenario in comparison to the pre-COVID scenario.

Table 5.11: Wind Proportion by Directional Sector for Pre-COVID and COVID Scenario

WIND PROPORTION (%)									
EPA Monitoring Station	**Scenario**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	Pre-COVID	4.54	4.40	11.70	8.44	13.64	27.54	24.26	5.47
	COVID	6.02	18.62	31.44	5.45	7.24	9.60	15.77	5.87
Blanchardstown	Pre-COVID	4.74	4.22	11.45	9.57	13.33	25.65	25.04	6.00
	COVID	6.79	18.64	30.68	6.13	6.83	8.88	15.41	6.64
Dún Laoghaire	Pre-COVID	4.79	4.17	11.39	9.83	13.28	25.21	25.22	6.12
	COVID	6.97	18.65	30.51	6.28	6.74	8.71	15.33	6.82
Pearse Street	Pre-COVID	4.78	4.13	11.26	10.28	12.82	24.85	25.65	6.23
	COVID	7.09	18.68	30.24	6.63	6.45	8.51	15.39	7.01
Rathmines	Pre-COVID	4.69	4.24	11.45	9.50	13.23	25.92	25.04	5.93
	COVID	6.67	18.65	30.74	6.12	6.81	8.96	15.51	6.55
Ringsend	Pre-COVID	4.81	4.10	11.21	10.48	12.74	24.54	25.79	6.32
	COVID	7.22	18.68	30.11	6.75	6.37	8.38	15.33	7.14
St. John's Road	Pre-COVID	4.71	4.21	11.40	9.73	13.08	25.65	25.22	6.01
	COVID	6.78	18.66	30.60	6.27	6.70	8.83	15.49	6.67
Swords	Pre-COVID	5.00	3.81	10.67	12.61	11.47	21.82	27.51	7.10
	COVID	8.29	18.77	28.76	8.19	5.36	7.20	15.08	8.35
Winetavern Street	Pre-COVID	4.75	4.17	11.32	10.02	12.94	25.23	25.45	6.13
	COVID	6.95	18.67	30.41	6.46	6.57	8.66	15.44	6.85
Emo Court	Pre-COVID	7.88	3.54	6.68	14.59	22.71	16.15	18.37	10.08
	COVID	15.72	16.20	15.84	13.00	10.94	6.84	11.32	10.13
Portlaoise	Pre-COVID	7.91	3.56	6.46	14.84	22.88	15.99	18.38	9.98
	COVID	15.89	16.33	15.03	13.47	11.06	6.81	11.38	10.05
Dundalk	Pre-COVID	5.42	3.70	11.87	11.65	14.68	21.04	23.54	8.08
	COVID	8.93	16.92	29.54	7.32	7.00	8.24	12.63	9.42
Kilkitt	Pre-COVID	5.61	3.73	12.34	10.94	16.36	21.85	19.96	9.21
	COVID	9.25	15.77	30.05	6.58	7.95	9.33	10.97	10.10


Ballyfermot (%)
Blanchardstown (%)
Dún Laoghaire (%)
Pearse Street (%)
Rathmines (%)
Ringsend (%)
St. John's Road (%)
Swords (%)
Winetavern Street (%)
Emo Court (%)
Portlaoise (%)
N
NE
E
SE
S
SW
W
NW
Pre-COVID Wind Proportion (%)
COVID Wind Proportion (%)

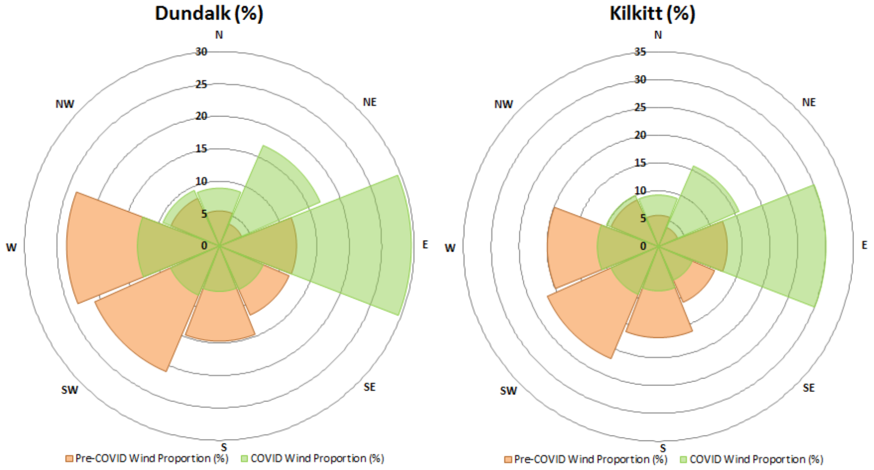


Figure 5.18: Wind Direction Proportion Roses Pre-COVID and COVID Scenarios

5.2.4. Vehicle Fleet Data

In the analysis of the 2016 to 2018 period presented in Section 3.3.5, the Irish Bulletin of Vehicle and Driver Statistics reports published by the Department of Transport, Tourism and Sport were used to determine the vehicle fleet (Department of Transport, Tourism and Sport, 2017; Department of Transport, Tourism and Sport, 2018; Department of Transport, Tourism and Sport, 2019). The statistics are published annually but the 2020 statistics were not published in time for this analysis; moreover as this analysis focused on a time period in the first half of 2020, use of the full annual report for that year would have confounded the results as the statistics would have included vehicles introduced in Ireland after the first lockdown period. The Department of Transport, Tourism and Sport (Department of Transport, Tourism and Sport, 2020) provided spreadsheets which contained details of every vehicle registered in Ireland by June 2020, which more accurately reflects the vehicle fleet present during the lockdown period. These spreadsheets were collated and the vehicle fleet breakdown by vehicle type, fuel type, engine capacity, Euro Class and unladen weight were calculated using the flow process shown in Figure 5.19.

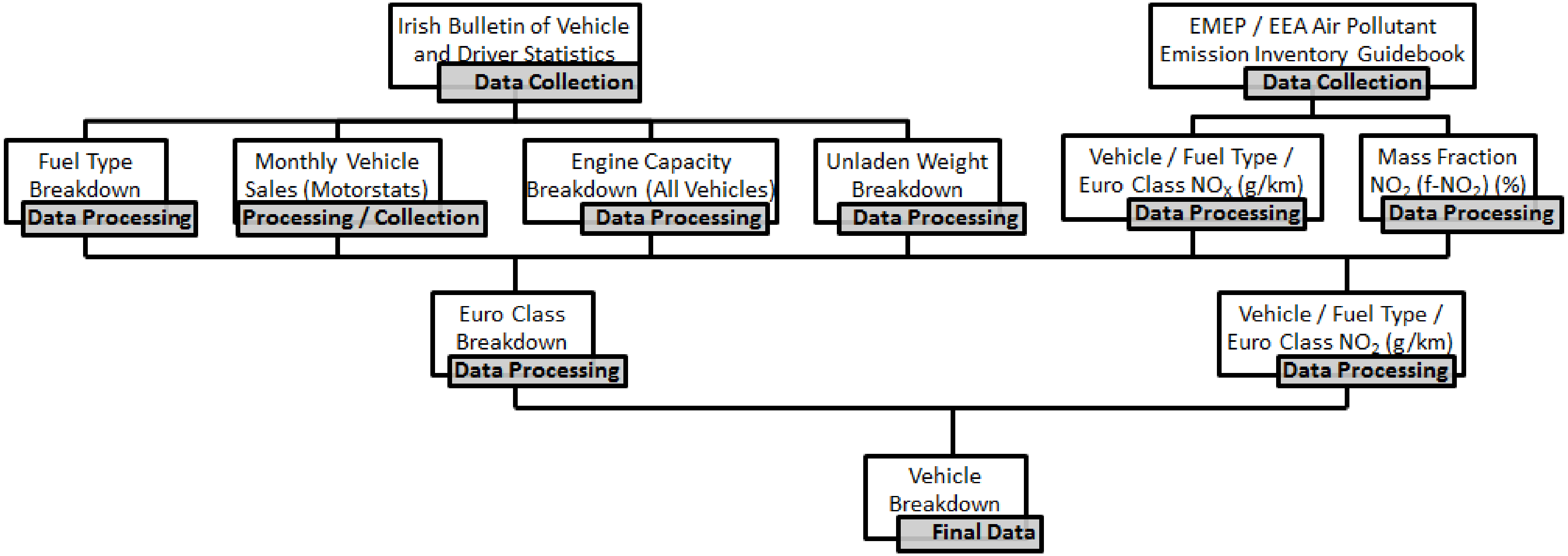


Figure 5.19: Vehicle Breakdown Analysis Flow Diagram

Table 5.12 presents the vehicle fleet breakdown by vehicle type during the COVID scenario and accounts for passenger cars, light commercial vehicles, heavy duty vehicles, small public service vehicles, large public service vehicles and motorcycles.

Table 5.12: Vehicle Type Breakdown COVID Scenario

Vehicle Type	Percentage of Overall Vehicle Fleet
Passenger Car (PC)	76.66%
Light Commercial Vehicle (LCV)	13.47%
Heavy Duty Vehicle (HDV)	1.48%
Small Public Service Vehicles (SPSV)	0.40%
Large Public Service Vehicle (LPSV)	0.72%
Motorcycle (M)	1.64%

Table 5.13 shows the fuel type breakdown for all vehicle types as of June 2020. Diesel was the pre-dominant fuel type for passenger cars, light commercial vehicles, heavy duty vehicles, small public service vehicles and large public service vehicles at 56.94%, 99.57%, 99.87%, 81.64% and 99.86%. Petrol was the most common fuel type in the motorcycle fleet at 99.58%, the second most common fuel type in the passenger car fleet at 39.40% and the third most common fuel type in the small public service vehicles at 5.70%. Hybrid petrol was the third most common fuel type in passenger cars at 2.75% and the second most common fuel type in the small public service vehicle fleet at 12.18%.

Table 5.13: Fuel Type Breakdown by Vehicle Type

Fuel Type	PC	LCV	HDV	SPSV	LPSV	M
Petrol	39.40%	0.21%	0.03%	5.70%	-	99.58%
Diesel	56.94%	99.57%	99.87%	81.64%	99.86%	0.15%
Electric	0.47%	0.16%	-	0.29%	-	0.18%
Hybrid Petrol	2.75%	-	-	12.18%	-	-
Hybrid Diesel	0.06%	-	-	0.19%	-	-
Ethanol	0.37%	-	-	0.00%	-	-
CNG	0.00%	-	-	0.00%	0.00%	-
LPG	0.00%	-	-	0.00%	-	-
Other	0.00%	0.05%	-	-	-	-

Table 5.14 defines the engine capacity ranges for the petrol, diesel and hybrid petrol fuel types in the passenger car and small public service vehicle fleets. Table 5.15 identifies the percentage breakdown for each engine size in the passenger car and small public service vehicle fleets. The small engine size, which represents vehicles with engine capacities between 1 000 and 2 000 cubic centimetres, was the most common size in all fuel types for both passenger cars and small public service vehicles. A number of significant differences were noticed between the breakdowns for both vehicle types, with 16.29% of petrol fuelled passenger cars within the mini engine size range whilst only 1.5% of petrol fuelled small public service vehicles were mini engines. Inversely, the percentages of medium and large petrol powered engines were greater for the small public service vehicles at 4.07% and 9.11% respectively, in comparison to 0.74% and 0.35% for the passenger cars. There were higher percentages of medium and large engine sizes in the hybrid petrol powered passenger cars at 17.12% and 3.37% respectively in comparison to 8.06% and 0.79% in the hybrid petrol powered small public service vehicles.

Table 5.14: Fuel Type / Engine Size Capacity Definitions

Fuel Type / Engine Size	Engine Capacity
Petrol Mini	≤1 000 cubic centimetres (c.c.)
Petrol Small	1 000 – 2 000 c.c.
Petrol Medium	2 000 – 3 000 c.c.
Petrol Large	≥3 000 c.c.
Diesel Small	≤2 000 c.c.
Diesel Medium	2 000 – 3 000 c.c.
Diesel Large	≥3 000 c.c.
Hybrid Petrol Small	≤2 000 c.c.
Hybrid Petrol Medium	2 000 – 3 000 c.c.
Hybrid Petrol Large	≥3 000 c.c.

Table 5.15: Engine Size Breakdown

Fuel Type	Engine Size	PC Percentage	SPSV Percentage
Petrol	Mini	16.29%	1.50%
	Small	82.63%	85.32%
	Medium	0.74%	4.07%
	Large	0.35%	9.11%
Diesel	Small	89.23%	85.14%
	Medium	10.72%	14.57%
	Large	0.05%	0.30%
Hybrid Petrol	Small	79.51%	91.15%
	Medium	17.12%	8.06%
	Large	3.37%	0.79%

Table 5.16 identifies the combined breakdown by fuel type and engine size for the passenger car fleet. Approximately half (50.81%) of the entire fleet were powered by small diesel engines and just under a third (32.55%) of all vehicles were powered by small petrol engines. The most common engine / fuel type combinations outside of these two main types were petrol mini, diesel medium and hybrid petrol small at 6.42%, 6.1% and 2.19% respectively.

Table 5.16: Passenger Car Full Fuel Type Engine Size Breakdown

Fuel Type	Engine Size	Fuel Type Percentage	Engine Size Percentage	Total Percentage
Petrol	Mini	39.40%	16.29%	6.42%
	Small		82.63%	32.55%
	Medium		0.74%	0.29%
	Large		0.35%	0.14%
Diesel	Small	56.94%	89.23%	50.81%
	Medium		10.72%	6.10%
	Large		0.05%	0.03%
LPG	All Sizes	0.00%	100%	0.00%
Hybrid Petrol	Small	2.75%	79.51%	2.19%
	Medium		17.12%	0.47%
	Large		3.37%	0.09%
Ethanol E85	All Sizes	0.37%	100%	0.37%
Electric	All Sizes	0.47%	100%	0.47%
Unaccounted Fuel Type (Diesel & Electric and Diesel Plug in Hybrid)	All Sizes	0.06%	100%	0.06%
Total		100.00%		100.00%

Table 5.17 identifies the combined breakdown by fuel type and engine size for the small public service vehicle fleet. Small diesel engines were the most common power source at 69.5% with diesel medium, hybrid petrol small and petrol small ranked second (11.89%), third (11.10%) and fourth (4.86%) most common respectively.

Table 5.17: SPSV Full Fuel Type Engine Size Breakdown

Fuel Type	Engine Size	Fuel Type Percentage	Engine Size Percentage	Total Percentage
Petrol	Mini	5.70%	1.50%	0.09%
	Small		85.32%	4.86%
	Medium		4.07%	0.23%
	Large		9.11%	0.52%
Diesel	Small	81.64%	85.14%	69.50%
	Medium		14.57%	11.89%
	Large		0.30%	0.24%
LPG	All Sizes	0.00%	100%	0.00%
Hybrid Petrol	Small	12.18%	91.15%	11.10%
	Medium		8.06%	0.98%
	Large		0.79%	0.10%
Ethanol E85	All Sizes	0.00%	100%	0.00%
Electric	All Sizes	0.29%	100%	0.29%
Unaccounted Fuel Type (Diesel & Electric and Diesel Plug in Hybrid)	All Sizes	0.19%	100%	0.19%
Total		100.00%		100.00%

Table 5.18 shows the unladen weight breakdown for the HDV fleet in Ireland as of June 2020. The majority (76.66%) of HDVs had an unladen weight between 3.5 and 7.5 tonnes with a further 13.47% within the 7.5 and 16 tonne range. Only 1.48% were within the 16 and 32 tonne range whilst 1.64% had an unladen weight in excess of 32 tonnes.

Table 5.18: HDV Unladen Weight Breakdown

HDV Unladen Weight	Percentage of HDV
<7.5 tonnes	76.66%
7.5 – 16 tonnes	13.47%
16 – 32 tonnes	1.48%
>32 tonnes	1.64%

The LPSV fleet within the vehicle registration spreadsheet did not specify the vehicle as being an urban LPSV or a coach and as the model of a number of LPSVs within the spreadsheet were unspecified; further research into the manufacturers was therefore required. Table 5.19 identifies the LPSV types that are mainly produced by each of the manufacturers and in certain cases, manufacturers produced both urban and coach LPSVs and these were accounted for by splitting the unspecified models equally amongst both LPSV types. Table 5.20 shows the breakdown of the LPSV fleet based on the LPSV type. Approximately 4 out of 5 (79.43%) of LPSVs are categorised as coaches whilst the remaining 20.57% were urban LPSVs.

Table 5.19: Unspecified LPSV Model Breakdown

LPSV Type	Manufacturers
Urban	Autosan, Alexander, BMC, Caetano, Cannon, Dennis, EOS, Iveco (50%), Leyland, MAN (50%), Omni City, Optare, Otokar, Transbus, VDL-DAF (50%), Volvo (50%), Wrightbus, Yutong (50%)
Coaches	Ayats, Beulas, Bova, Citroen, DAF, Erduman, EVM, EVM Ltd., Ferqui, Fiat, Ford, Gopo Train, Higer, Irizar, Isuzu, Iveco (50%), King Long, Landrover, LDV, LDV/DAF, MAN (50%), Marbus, Mellor, Mercedes, Neoplas, Nissan, Nu-Track, Opel, Peugeot, Plaxton, Renault, Scania, Setra, Sitcar, Sunsundegui, Tam Durabus, Tekaydinlar, Temsa, Toyota, Turas, Unvi, Vanhool, Vauxhall, VDL, VDL-DAF (50%), Volkswagen, Volvo (50%), Yutong (50%)

Table 5.20: LPSV Type Breakdown

LPSV Type	Percentage of LPSV
Urban	20.57%
Coaches	79.43%

Table 5.21 identifies the breakdown by engine capacity for all motorcycles as of June 2020. Approximately half (49.8%) of all motorcycles had an engine capacity in excess of 750 cubic centimetres (c.c.) with a further 32.55% of motorcycles within the 250 and 750 c.c. range. A small percentage (1.24%) of vehicles within the motorcycle fleet were categorised as mopeds and 1.03% had an engine capacity less than 50 c.c. and the remaining 0.21% had a capacity greater than 50 c.c.

Table 5.21: Motorcycle Engine Capacity Breakdown

Motorcycle Engine Capacity	Percentage of Motorcycles
<50 c.c. Moped	1.03%
>50 c.c. Moped	0.21%
<250 c.c. Motorcycle	16.41%
250 – 750 c.c. Motorcycle	32.55%
>750 c.c. Motorcycle	49.80%

The year of registration was then analysed to determine the Euro Classification breakdown within each fuel type / engine size / unladen weight / engine capacity category for every vehicle type. Table 5.22 and Table 5.23 identify the Euro Class breakdown within each fuel type / engine size combination for both passenger cars and small public service vehicles. The most noticeable trend in both vehicle types was the larger proportion of Euro 3 and Euro 4 vehicles within the larger engine sizes, particularly the medium and large petrol engines and large diesel engines. In the passenger car fleet, 73.53% of medium petrol, 68.79% of large petrol and 66.72% of large diesel vehicles were Euro 3 or Euro 4 vehicles. In the small public service vehicles fleet, 67.39% of medium petrol, 69.9% of large petrol and 89.58% of large diesel vehicles were Euro 3 or Euro 4. Newer fuel type / engine size combinations such as petrol mini and diesel small which were introduced since the introduction of Euro 4 vehicles had varied distributions. Euro 6 was the most common euro class for mini petrol powered vehicles in both the passenger cars and small public service vehicles at 59.35% and 100% respectively whilst Euro 5 was the most common class in the small diesel vehicles at 44.31% and 59.63% respectively.

Table 5.22: Passenger Car Euro Class Breakdown

Euro Class	Petrol				Diesel			Ethanol	CNG	LPG
	Mini	Small	Medium	Large	Small	Medium	Large			
Pre-Euro	-	0.19%	1.33%	0.86%	-	0.04%	0.34%	-	-	2.90%
Euro 1	-	0.46%	3.53%	2.16%	-	0.11%	1.02%	-	-	0.00%
Euro 2	-	3.41%	8.03%	8.24%	-	0.26%	1.70%	-	-	0.00%
Euro 3	-	22.29%	33.56%	26.67%	-	3.89%	20.88%	-	-	10.14%
Euro 4	18.30%	41.14%	39.97%	42.12%	24.13%	25.98%	45.84%	70.67%	100.00%	5.80%
Euro 5	22.36%	16.73%	3.85%	10.72%	44.31%	42.41%	16.16%	29.33%	0.00%	41.23%
Euro 6	-	-	-	-	-	-	-	0.00%	0.00%	39.93%
Euro 6 (≤2016)	9.98%	4.75%	2.74%	2.36%	11.71%	10.22%	3.20%	-	-	-
Euro 6 (2017 – 2019)	42.07%	9.99%	6.41%	6.35%	18.06%	16.18%	8.66%	-	-	-
Euro 6 (2020+)	7.30%	1.05%	0.60%	0.51%	1.80%	0.91%	2.21%	-	-	-

Table 5.23: Small Public Service Vehicles Euro Class Breakdown

Euro Class	Petrol Mini	Petrol Small	Petrol Medium	Petrol Large	Diesel Small	Diesel Medium	Diesel Large
Pre-Euro	-	0.41%	6.52%	11.65%	-	0.72%	-
Euro 1	-	0.31%	2.17%	1.94%	-	0.08%	-
Euro 2	-	0.62%	10.87%	9.71%	-	1.32%	-
Euro 3	-	7.46%	32.61%	25.24%	-	9.19%	70.83%
Euro 4	-	56.06%	34.78%	44.66%	12.79%	26.77%	18.75%
Euro 5	0.00%	22.17%	10.72%	4.85%	59.63%	45.42%	8.19%
Euro 6 (≤2016)	23.53%	6.84%	2.32%	0.97%	12.05%	7.27%	2.23%
Euro 6 (2017 – 2019)	76.47%	6.11%	-	-	14.86%	9.11%	-
Euro 6 (2020+)	-	-	-	0.97%	0.67%	0.12%	-

Table 5.24 shows the Euro class breakdown for the petrol and diesel light commercial vehicles. The breakdown was significantly different for the petrol and diesel fuel types, with a higher percentage (61.95%) of petrol LCVs classed as Euro 3 or Euro 4 whilst the proportion of diesel LCVs was more equally split across Euro classes. 17.49% of diesel LCVs were Euro 3, 25.58% were Euro 4, 28.44% were Euro 5 and 24.59% were classed as one of the Euro 6 classes. Only 3.88% of diesel LCVs were pre-Euro 3 whilst 21.64% of petrol LCVs were pre-Euro 3.

Table 5.24: Light Commercial Vehicles Euro Class Breakdown

Euro Class	Petrol	Diesel
Pre-Euro	5.36%	0.28%
Euro 1	7.04%	0.95%
Euro 2	9.24%	2.65%
Euro 3	39.39%	17.49%
Euro 4	22.56%	25.58%
Euro 5	6.82%	28.44%
Euro 6 (≤2017)	2.66%	8.53%
Euro 6 (2018 – 2020)	6.94%	16.06%

Table 5.25 identifies the Euro Class breakdown by unladen weight range for all HDVs as of June 2020. Euro VI was the most common class across all unladen weight ranges at 28.81% of diesel HDVs less than 7.5 tonnes, 43.94% of diesel HDVs within 7.5 and 16 tonnes, 70.25% of diesel HDVs within 16 and 32 tonnes and 57.5% of diesel HDVs greater than 32 tonnes. Higher percentages of vehicles within the newer Euro Classes (Euro V and Euro VI) for HDVs in comparison to the passenger cars, small public service vehicles and LCVs would be expected as the last updates in HDVs occurred in 2008 and 2013 for Euro V an Euro VI respectively, whilst in the same time period four updates were introduced for passenger cars / small public service vehicles and three updates were introduced for LCVs.

Table 5.25: Heavy Duty Vehicles Euro Class Breakdown

Euro Class	Diesel <7.5 tonnes	Diesel 7.5 – 16 tonnes	Diesel 16 – 32 tonnes	Diesel >32 tonnes
Pre-Euro	0.27%	0.05%	-	-
Euro I	1.12%	0.25%	0.03%	-
Euro II	4.98%	1.36%	0.32%	-
Euro III	19.17%	9.35%	2.73%	5.00%
Euro IV	22.84%	20.33%	8.75%	2.50%
Euro V	22.81%	24.72%	17.92%	35.00%
Euro VI	28.81%	43.94%	70.25%	57.50%

Table 5.26 shows the Euro Class breakdown for LPSVs based on the LPSV type. Similar to the HDVs the majority of vehicles were classified as one of the newer Euro Classes (Euro V or Euro VI) due to the limited number of updates to the Euro Classes with the last update introduced in 2013. There was a considerable difference between the LPSV types as the percentage of Euro VI urban LPSVs was 55.2% and only 26.58% of coaches were Euro VI. The percentage of pre-Euro III vehicles in urban LPSVs and coaches were similar at 2.18% and 1.95% respectively.

Table 5.26: Large Public Service Vehicles Euro Class Breakdown

Euro Class	Urban	Coaches
Pre-Euro	0.09%	0.05%
Euro I	0.21%	0.21%
Euro II	1.88%	1.69%
Euro III	12.68%	17.40%
Euro IV	15.29%	27.74%
Euro V	14.65%	26.32%
Euro VI	55.20%	26.58%

Table 5.27 shows the Euro Class breakdown for all engine capacity ranges for the motorcycle fleet. The last euro class update for motorcycles of importance for our analysis was Euro III as all classes after Euro III are assigned the same emission rate in the Emission Inventory Guidebook; therefore are grouped together under Euro III below. This class was introduced 13 years prior to the first COVID lockdown period in 2007. Similar to the HDVs and LPSVs, due to the substantial time period since the Euro III, a large proportion of vehicles within each of the engine capacity ranges are classified as a newer

Euro Class. The percentage of mopeds with engine capacities less than 50 c.c., which were also classified as Euro III, was 61.25%, whilst 92.54% of mopeds greater than 50 c.c. were classified as Euro III. Euro III was the most common class for motorcycles also, accounting for 57.15% of motorcycles less than 250 c.c., 39.23% of motorcycles between 250 and 750 c.c. and 45.01% of motorcycles greater than 750 c.c.

Table 5.27: Motorcycles Euro Class Breakdown

Euro Class	<50c.c. Mop.	>50c.c. Mop.	<250c.c. Mot.	250 – 750c.c. Mot.	>750c.c. Mot.
Pre-Euro	8.03%	4.49%	13.13%	19.10%	14.96%
Euro I	11.71%	0.00%	20.76%	29.45%	28.35%
Euro II	19.01%	2.96%	8.96%	12.23%	11.69%
Euro III	61.25%	92.54%	57.15%	39.23%	45.01%

The vehicle fleet breakdown for the pre-COVID scenario was based on the 2019 statistics which were retrieved from the Irish Bulletin of Vehicle and Driver Statistics (Department of Transport, Tourism and Sport, 2020) and the procedure used to determine the vehicle fleet breakdown was the same as that described in Section 3.3.4.

5.2.5. Road Density and Land Use Data

The road density data used for this analysis was obtained from the National Transport Authority's model for the east region of Ireland (National Transport Authority, 2020). This contained information in relation to all links located in the province of Leinster, and was the same data used for the analysis of the performance of the ambient NO_2 concentration model during the 2016 to 2018 period, described in Section 3.3.4. The effects of the COVID lockdown restrictions on the values of this predictor variable were assumed to be negligible as changes in the road network during the short period from 2018 to 2020 would be minor as the majority of transport projects would typically be realignments, resulting only in minor changes in overall lengths of links.

In relation to the land use data, the majority of the stations analysed in the COVID scenario analysis were located in cities and were mainly categorised as non-agricultural areas, whilst a number of other stations were in rural areas, of which a substantial area surrounding the stations were categorised as agricultural. Over the short period between 2018 and the beginning of 2020, any change in the categorisation of the lands surrounding the air quality monitoring stations was assumed to be limited and would have minimal effect on the model results.

5.3. Unique Scenario / Environment (COVID Lockdown) Analysis Results

This section provides details of the results of the COVID lockdown analysis described in Section 5.2. These results include a comparison of measured and modelled concentrations during the COVID lockdown period, comparison of measured and modelled concentration differences between the pre-COVID and COVID scenarios and concentration changes due to the changes in each of the predictor variables.

5.3.1. Comparison of Measured and Modelled COVID Concentrations

In Figure 5.20, Figure 5.21 and Figure 5.22 modelled mean concentrations and standard error ranges are compared with average measured concentrations at various EPA monitoring locations during the COVID lockdown period (28th March 2020 to 17th May 2020). As can be seen in Figure 5.20, the modelled results compare reasonably well with the measured concentrations at the Kilkitt, Monaghan monitoring station; a rural location. However, the model overestimated the concentrations at all other stations except at the Ringsend, Dublin monitoring station, where the model underestimated by approximately 4.4 µg/m^3. The Ringsend result was similar to the results achieved in the analysis of 2016, 2017 and 2018 reported in Chapter 3, whereby the model also underestimated measured NO_2 concentrations. This underestimation of concentrations at Ringsend highlights that other sources of NO_2 not captured by the variables in the model are present; these sources were identified in Section 5.1.3 as part of the discussion of results presented in Figure 5.1. In any normal distribution of data, 95% of data points should be within two standard error ranges (University of Pennsylvania, Penn Arts & Sciences, 2021; Statology, 2019) and 100% of data points should be within three standard error ranges but for this analysis only 43% of data points (6 of 14 stations) were within two standard error ranges, as shown in Figure 5.21, whilst 100% of data points were within three standard error range, as shown in Figure 5.22. In Section 5.1 it was presented that the model typically overestimated the concentrations at the majority of locations but the measured concentrations were captured by the standard error ranges of the model. In the model, the lower the concentration the smaller the standard error ranges that are produced, as identified by the rural locations in Figure 5.21. Therefore in a scenario such as the COVID lockdown period where locations experienced significant reductions in pollution and the model accurately estimates the reduction in concentration, the difference between modelled and measured concentrations would be the same as the difference between the measured and modelled concentrations from the pre-COVID scenario. The significant detail that is impacted by this scenario is the size of the standard error ranges which would have reduced considerably and as a result the measured concentration may no longer be within the standard error ranges of the modelled concentrations.

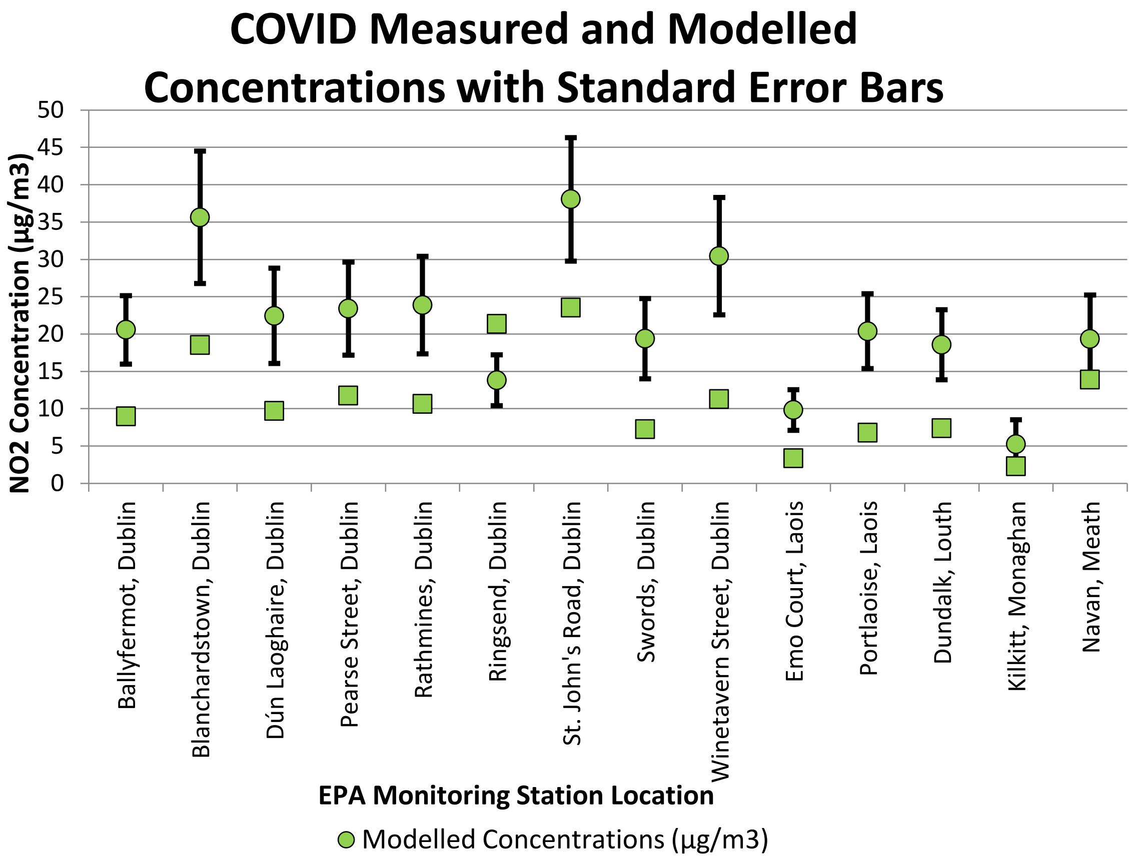


Figure 5.20: COVID Measured and Modelled Concentrations with Standard Error Bars

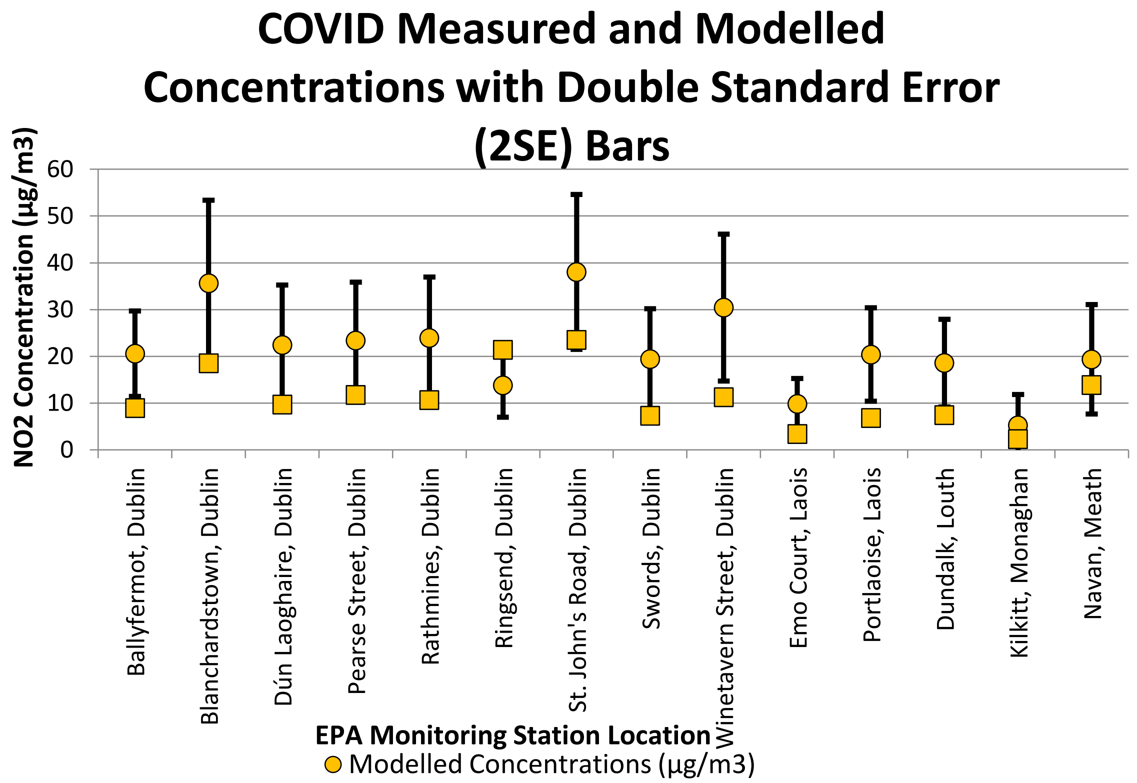


Figure 5.21: COVID Measured and Modelled Concentrations with Double Standard Error (2SE) Bars

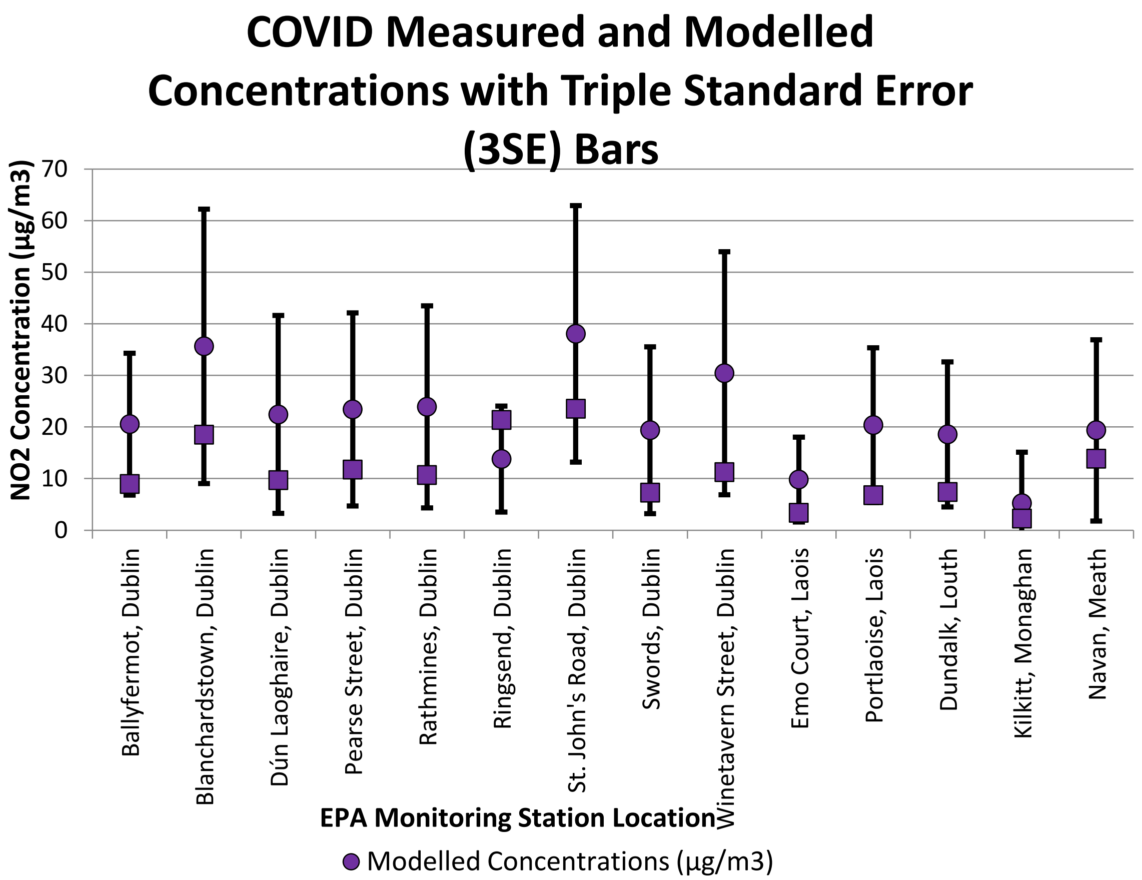


Figure 5.22: COVID Measured and Modelled Concentrations with Triple Standard Error (3SE) Bars

The original study of 2010 to 2012 captured 78% of the spatial variability in NO_2 with a cross validation R^2 of 77.4% (Naughton et al., 2018) and this accuracy was retained in the analysis of 2016, 2017 and 2018, reported in Chapter 3 and Section 5.1. Figure 5.23 shows that the cross validation R^2 is significantly lower in the first COVID lockdown period analysis at 44.03%. However, this result was strongly influenced by the measurement at Ringsend, Dublin as shown in Figure 5.23. The cross validation R^2 improves considerably to 82.27% when the outlier at Ringsend is excluded, as shown in Figure 5.24.

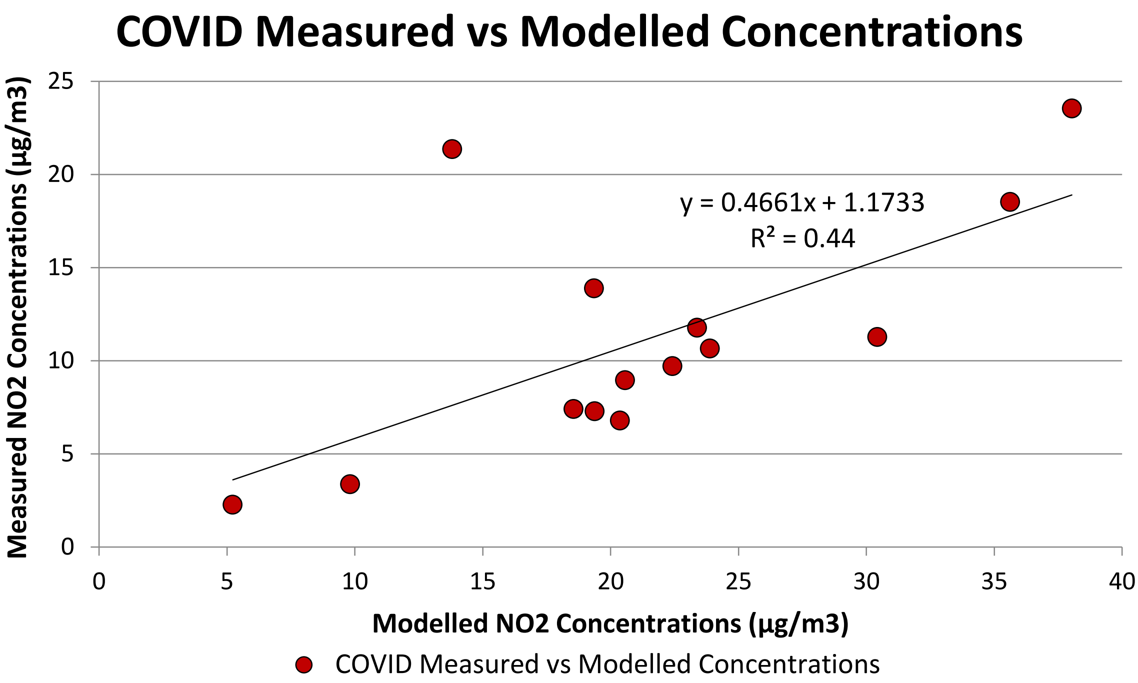


Figure 5.23: COVID Measured vs Modelled Concentrations

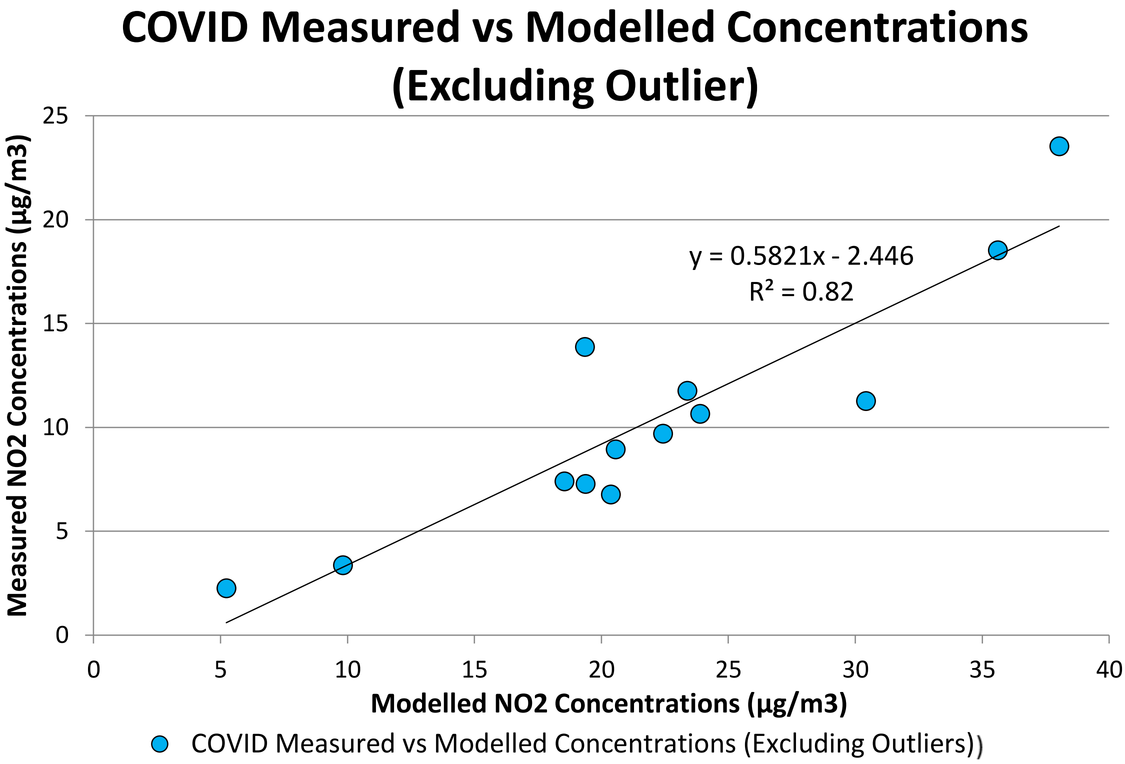


Figure 5.24: COVID Measured vs Modelled Concentrations (Excluding Outlier)

5.3.2. Comparison of pre-COVID and COVID Concentrations

The modelled concentrations presented above display greater differences between the pre-COVID and COVID scenarios than are observed in the measured concentrations, as shown in Figure 5.25. The modelled difference shown in Figure 5.25 represents the difference between the pre-COVID modelled concentration and the modelled COVID scenario concentration, which were calculated using the WS-LUR model. The measured difference represents the difference between measured pre-COVID concentration and the measured COVID scenario concentration, both of which represented average daily concentrations which were calculated using the hourly data made available by the EPA on their SAFER database website (Environmental Protection Agency, 2019). The modelled concentrations overestimated the difference by 50 – 253% at the majority of the monitoring stations with the outlier at Ringsend overestimating by 413%. For the COVID scenario, the modelled concentrations were significantly closer to the measured concentrations in comparison to measured and modelled concentrations for the pre-COVID scenario. The overestimation of the change in concentrations at the majority of the stations could be due to a number of factors relating to the unique conditions being examined, the development of the original model or the assumptions introduced in the COVID analysis. The exclusion of the minor route flows resulted in increased modelled concentration differences as it was estimated that concentration reductions due to this assumption were in the range 5.1 and 9.4 μg/m^3 (described in further detail in Section 5.3.3). The flows on minor routes would not have reduced as significantly as assumed in this analysis as flows would not have stopped completely on these routes. Therefore the difference between the pre-COVID and COVID modelled concentrations would have been closer to the difference between pre-COVID and COVID measured concentrations if actual flows for minor routes would have been available for the entire COVID lockdown period.

Considering the development of the model, it is recalled that the first predictor variable in the final version of the regression model was included based on the highest cross validation R^2. Other predictor variables were only included if the R^2 increased by 1% or more and the direction of effect of the variables already included in the model did not change due to the inclusion of the additional variable (Naughton et al., 2018). The commercial properties predictor variable mainly reflects the number of commercial properties surrounding a study location, but an unknown proportion of this variable captures the effects of the other variables, such as residential property numbers, which were not included as independent predictor variables as they did not satisfy the above selection criteria. As the lockdown conditions were significantly different to those under which the original model was calibrated, the commercial properties variable is unlikely to capture the effects of those other variables in the same way. Therefore, for the COVID analysis the modelled reduction in commercial properties may be somewhat less than the full reduction observed during the lockdown period to allow for the continued influence of other variables not included in the model, e.g. residential properties, for which activity was not reduced. This approach would be expected to lead to smaller differences between modelled pre-COVID concentrations and modelled COVID concentrations, particularly in more urban environments.

Considering the unique conditions being examined during the COVID lockdown period weather conditions were significantly different to those experienced during the model calibration period and in the earlier study years of 2016-18, as discussed in Section 5.2.3. The pre-dominant wind direction during the lockdown period was from an easterly direction, whilst during the other periods (including the pre-COVID period), the pre-dominant wind direction was from a westerly / south-westerly direction. A pre-dominant westerly / south-westerly wind would bring relatively unpolluted air from the Atlantic Ocean whilst an easterly wind direction would bring air across from continental Europe and the United Kingdom, which could contain higher concentrations of pollutants (Donnelly, Misstear, & Broderick, 2011). As a consequence the measured reductions in concentrations during the lockdown period are likely to have been smaller than would have been experienced with annual average wind directions. This indicates that the full impact of reduced local emissions is not evident in the measured difference values shown in Figure 5.25 due to a concurrent increase in background concentrations.

The WS-LUR model can only partially capture the effects of atypical short-term meteorological conditions on average background concentrations. Any increase in background concentrations should be reflected in a higher value for the constant in the ambient NO_2 concentration model (α_0). However, the model calibration process provides just a single annual average value that is applied uniformly across the entire country. On the other hand, the WS-LUR model did capture the effects of the COVID period wind directions on the predictor variables within the model as these are weighted based on the wind direction proportions experienced during the particular study period being analysed.

Table 5.28: Measured and Modelled Pre-COVID and COVID NO_2 Concentrations

Monitoring Station	Measured Pre-COVID Conc. (μg / m^3)	Modelled Pre-COVID Conc. (μg / m^3)	Measured COVID Conc. (μg / m^3)	Modelled COVID Conc. (μg / m^3)
Ballyfermot, Dublin	20	33.5	11.8	16.0
Blanchardstown, Dublin	31	39.9	20.4	20.4
Dún Laoghaire, Dublin	15	22.7	10.5	11.3
Pearse Street, Dublin	49	37.8	14.6	13.5
Rathmines, Dublin	22	30.5	13.3	12.7
Ringsend, Dublin	24	21.2	21.7	11.7
St. John’s Road, Dublin	43	33.9	25.0	24.7
Swords, Dublin	15	21.8	8.2	11.7
Winetavern Street, Dublin	28	43.8	13.3	16.5
Emo Court, Laois	5.5	9.2	4.1	9.8
Portlaoise, Laois	11.2	17.1	7.8	12.7
Dundalk, Louth	13.6	19.8	8.1	12.2
Kilkitt, Monaghan	3.4	4.8	2.4	5.2

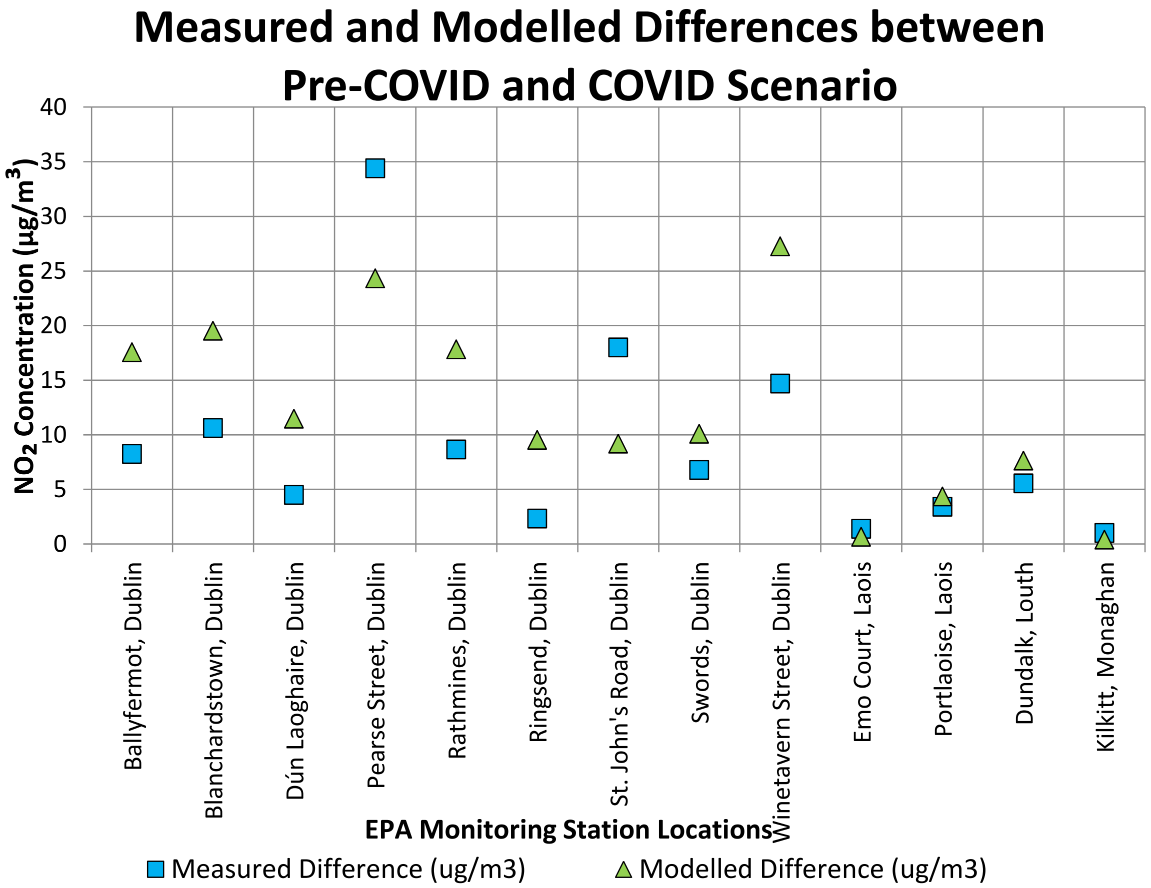


Figure 5.25: Measured and Modelled Differences between Pre-COVID and COVID Scenario

5.3.3. Analysis of the Individual Predictor Variables

The reasons underlying the trends evident in Figure 5.25 were investigated in more detail. Table 5.29 and Figure 5.26 present the separate impacts of each individual modelled COVID condition on 2019 concentrations. The modelled conditions considered were (i) a reduction in commercial property numbers, (ii) a reduction in major route traffic, (iii) the weather conditions experienced during COVID lockdown and (iv) the exclusion of minor route traffic.

Commercial property numbers: The model results show that the reduction in commercial property numbers to the extent experienced during the lockdown period leads to corresponding reductions in modelled NO_2 concentrations of between 0.2 and 6.0μg/m^3. The larger concentration reductions occur mainly in city centre locations whilst the concentration changes predicted in rural / suburban areas are smaller.

Traffic: The combined reduction in major route flows to the levels measured during the lockdown period, and the exclusion of all minor route traffic resulted in reductions in modelled concentrations of between 1.0 and 10.7μg/m^3. The smallest reductions were in locations where the majority of surrounding routes were of major route standard (national route or motorway) that experienced minimal reductions in traffic flows during the lockdown period. Conversely the largest reductions occur in locations dominated by minor route traffic. As traffic count data was not available for these routes for the lockdown period, all minor route flows were excluded from the calculation of the Inverse Distance Weighted Vehicle Kilometres Travelled variable. The impact of this approach was quantified by excluding the minor route flows from an analysis of 2019 concentrations, while keeping all other variables (including major route flows) unchanged. The observed reductions in modelled NO_2 concentrations (presented in Table 5.29 as Minor Traffic Excluded) ranged between 2.9 and 9.4μg/m^3, with the largest reductions occurring at city centre locations where the majority of routes are of lower standard (i.e. minor routes) but have considerable average daily flows. The Minor Traffic Excluded concentration changes shown in Figure 5.26 identify the maximum reduction in concentrations that can occur based on minor route traffic (e.g. from normal traffic conditions to no traffic) at each of the monitoring station locations. The actual concentration change experienced during the COVID lockdown due to the minor route traffic would be less than the values shown in Table 5.29 and Figure 5.26 as traffic on minor routes did not stop entirely during this time period. The modelled differences shown in Figure 5.25 would also be reduced and therefore, would be closer to the measured differences.

Weather: The effects of the weather experienced during COVID lockdown period were quantified by retaining the 2019 conditions for all variables in the model except the wind proportions and average wind speeds, which were altered to reflect COVID conditions. The weather conditions experienced during COVID would have resulted in increases in concentrations at 7 of the 11 monitoring station locations if they had occurred in 2019, as shown in Table 5.29. The average change in concentration due to the weather conditions experienced during COVID was 0.7μg/m^3. The effects of weather conditions experienced during lockdown varied considerably with a concentration reduction of 5.2μg/m^3 at Ballyfermot, whilst the concentration at St. John's Road increased by 7.7μg/m^3. The large increase in NO_2 at St. John's Road was mainly due to the change in wind direction proportions in comparison to the proportions experienced during 2019. The predominant wind direction during 2019 was from a westerly direction whilst during the lockdown period the predominant wind direction was from an easterly direction, which was also the direction in which most of the traffic and roads are located at this site, as described in Section 5.2.1.

The individual impacts of the reduction in commercial property numbers and the exclusion of minor traffic display similar trends across the locations analysed, as shown in Figure 5.26. The effect of excluding the minor traffic is approximately 4 – 5 μg/m^3 larger than the effect of reducing the commercial properties across all stations. This highlights the potential for confounding within the predictor variables. The two variables may be linked in localised areas, for example, if the commercial properties are closed in an area the flows on the minor routes could reduce due to this closure and their impact would be captured twice in the analysis. Therefore, the COVID Commercial Properties and Minor Traffic Excluded scenarios in Table 5.29 were checked for correlation. The values for these variables for all wind directional sectors at all monitoring stations were compared for the COVID modelled scenario, the pre-COVID (2019) modelled scenario and the percentage change in values from pre-COVID (2019) to the COVID lockdown period, producing Pearson Correlation Coefficients of -0.055, 0.2217 and 0.1103 respectively, highlighting that the variables are not correlated.

Table 5.29: COVID Conditions Individual Impacts on 2019 Concentrations

Monitoring Station	2019 Model. Conc. (μg / m^3)	Changes	2019 Scenario with Change (μg / m^3)	Conc. Difference (μg / m^3)
Ballyfermot, Dublin	33.5	COVID Comm. Prop.	33.4	-0.2
		COVID Maj. Route Traff. Only	23.7	-9.8
		COVID Weather	28.4	-5.2
		Minor Traffic Excluded	28.4	-5.1
Blanchardstown, Dublin	39.8	COVID Comm. Prop.	39.5	-0.3
		COVID Maj. Route Traff. Only	38.8	-1.0
		COVID Weather	40.8	1.0
		Minor Traffic Excluded	33.7	-6.1
Coleraine Street, Dublin	39.9	COVID Comm. Prop.	35.0	-4.9
		COVID Maj. Route Traff. Only	31.8	-8.2
		COVID Weather	41.7	1.7
		Minor Traffic Excluded	30.6	-9.4

Monitoring Station	**2019 Model. Conc. (µg / m³)**	**Changes**	**2019 Scenario with Change (µg / m³)**	**Conc. Difference (µg / m³)**
Davitt Road, Dublin	34.8	COVID Comm. Prop.	34.3	-0.5
		COVID Maj. Route Traff. Only	24.1	-10.7
		COVID Weather	34.4	-0.4
		Minor Traffic Excluded	26.3	-8.5
Dun Laoghaire, Dublin	22.7	COVID Comm. Prop.	22.3	-0.5
		COVID Maj. Route Traff. Only	18.6	-4.1
		COVID Weather	25.3	2.6
		Minor Traffic Excluded	19.8	-2.9
Pearse Street, Dublin	38.0	COVID Comm. Prop.	32.0	-5.9
		COVID Maj. Route Traff. Only	29.8	-8.2
		COVID Weather	37.0	-1.0
		Minor Traffic Excluded	28.8	-9.2
Rathmines, Dublin	30.5	COVID Commercial Properties	29.9	-0.6
		COVID Major Route Traffic Only	24.4	-6.2
		COVID Weather	31.9	1.4
		Minor Traffic Excluded	24.0	-6.5
Ringsend, Dublin	21.4	COVID Comm. Prop.	21.0	-0.3
		COVID Maj. Route Traff. Only	14.7	-6.6
		COVID Weather	18.1	-3.3
		Minor Traffic Excluded	14.6	-6.7
St. John’s Road, Dublin	34.1	COVID Comm. Prop.	32.9	-1.2
		COVID Maj. Route Traff. Only	27.9	-6.2
		COVID Weather	41.8	7.7
		Minor Traffic Excluded	26.2	-7.8
Swords, Dublin	21.8	COVID Comm. Prop.	21.4	-0.3
		COVID Maj. Route Traff. Only	17.4	-4.4
		COVID Weather	23.1	1.3
		Minor Traffic Excluded	17.9	-3.8
Winetavern Street, Dublin	44.0	COVID Comm. Prop.	38.3	-5.7
		COVID Maj. Route Traff. Only	35.4	-8.5
		COVID Weather	46.2	2.2
		Minor Traffic Excluded	34.6	-9.4

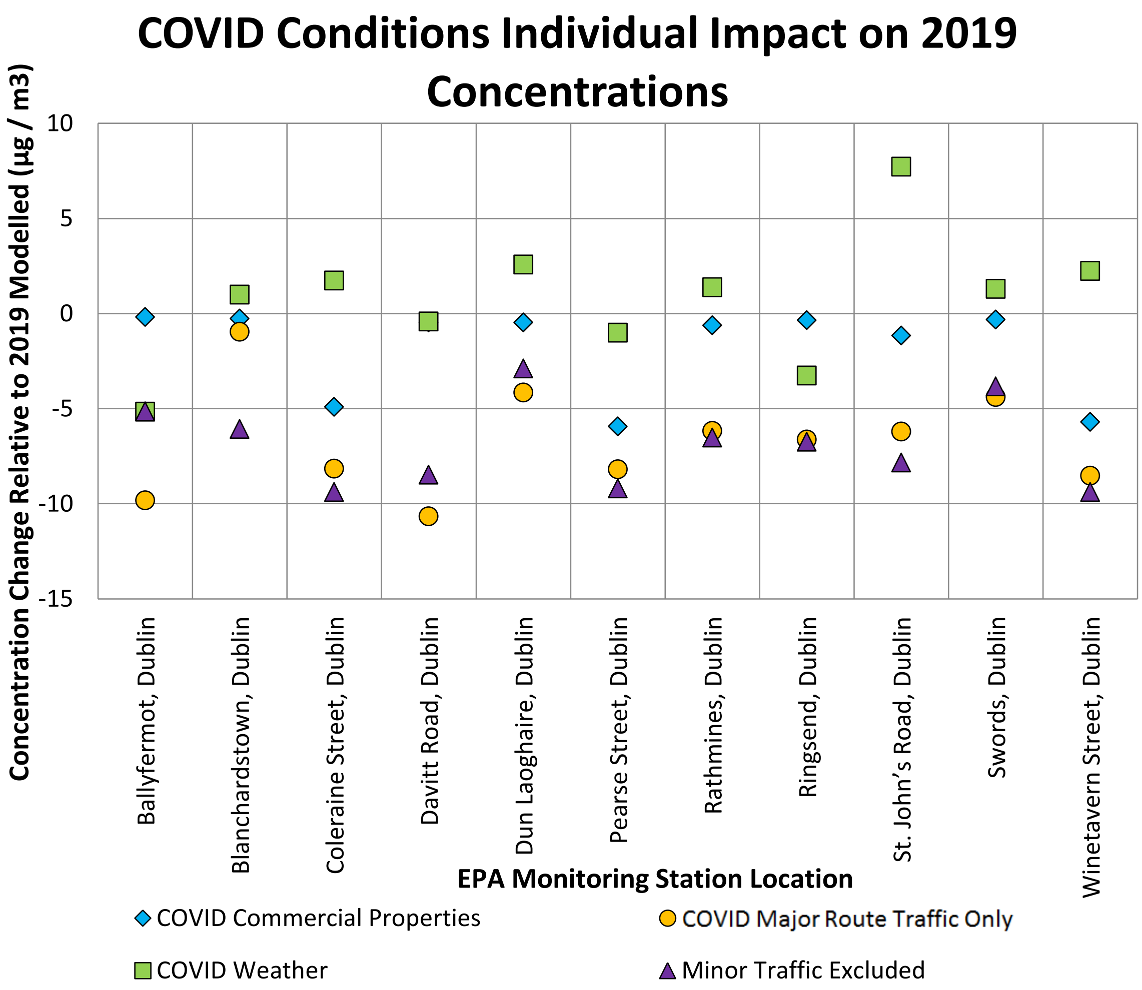


Figure 5.26: COVID Conditions Individual Impact on 2019 Concentrations

5.3.4. COVID Analysis Conclusions

The analysis of the effects of individual predictor variables on modelled concentrations assist with decisions on the mitigation measures that should be implemented at particular monitoring stations. These results identified the likely changes in concentrations that can be achieved by measures targeting these variables across all monitoring stations. The combined reduction in major route traffic and exclusion of minor route traffic had the greatest impact on NO_2 with concentration reductions across all monitoring stations ranging from -1.0 and -10.7 $\mu g/m^3$. Reductions in commercial property numbers were also effective in reducing NO_2 concentrations by between -0.2 and -5.9 $\mu g/m^3$ with the largest impacts in city centre locations where businesses and services are most densely populated. The effects of different weather conditions varied considerably between monitoring stations with concentration changes ranging between +7.7 and -5.2 $\mu g/m^3$. The weather is not a measure which can be controlled but it can be used to identify sources of pollution such as roads and traffic.

5.4. Conclusion

The accuracy of approximately 76% (cross-validation R^2) achieved by the original and new model methodologies under normal conditions (2016 to 2018 analysis) aligns with the strongest results for other LUR models developed throughout Europe which achieved cross validation R^2 between 55% and 92% (Beelen et al., 2013). These results were also equal to the level of accuracy achieved by advanced dispersion models, with cross validation R^2 values between 4% and 82% and have significantly greater data requirements and complexity (Briggs, 2005; Benson, 1992; Karppinen et al., 2000; Kukkonen et al., 2001). This was a significant result as the model accuracy of 76% was largely unaffected despite the considerable period of time that has passed since the original development of the model and the significant changes that would have occurred over this time period such as increased traffic levels as well as potential changes in land use and commercial property numbers. The validation of the new model methodologies are positive results as the WS-LUR model now has the capability of accounting for different vehicle fleet compositions surrounding a study location and it also provides an opportunity to analyse concentration changes due to changes in vehicle fleet breakdown or fuel type changes within the fleet.

The unique scenario / environment (COVID analysis) highlighted the capability of the model to identify the proportion of the concentration change that was linked to each of the predictor variable changes. The Ringsend station was the outlier in the COVID analysis as the modelled concentration was below the measured concentration. This underestimation in concentration was attributed to a number of NO_2 sources not captured by the predictor variables in the model. These include operations at Dublin Port (land and sea traffic towards the port) and the Poolbeg Generating Station, both of which would be at or near full operation even during the COVID lockdown period. Excluding the Ringsend outlier increased the cross-validation R^2 from 44% to 82%. The COVID analysis provided a useful insight into the accuracy of the model when altering values of the predictor variables as actual measured pollutant data was available for pre- and post-scenario comparisons.

The accuracy of the model in estimating concentrations and changes in concentrations due to changes in predictor variable values provides confidence in the use of the model to investigate mitigation measures and their potential improvements in air quality. The mitigation measures which are best suited for analysis using the model would target one or a number of the predictor variables within the WS-LUR equation. Therefore these mitigation measures would focus on changing the IDWVKT, road density, commercial properties, agricultural / natural land use and wind conditions surrounding a study location. The COVID analysis identified the potential improvements in air quality that could be achieved by altering a number of these variables, such as:

- Reductions in the range of 0.2 and 5.9 $\mu g/m^3$ with the closure / reduction of a number of commercial properties surrounding a study location
- Reductions between 2.9 and 9.4 $\mu g/m^3$ with measures targeting vehicle flows on minor routes only
- Reductions in the range of 1.0 and 10.7 $\mu g/m^3$ with measures targeting vehicle flows on major routes only
- Changes of -5.2 and +7.7 $\mu g/m^3$ due to changes in weather conditions at a study location

Chapter 6 provides details and results of a number of mitigation measures which were analysed using the WS-LUR model and targeted one or a number of the predictor variables within the model.

6. NO_2 Mitigation Measures

This chapter of the thesis describes the procedure and results of an analysis carried out on various mitigation measures using the Wind Sector-Land Use Regression (WS-LUR) model developed in Chapter 3. A number of locations in Ireland were continuously recording annual mean concentrations close to the WHO annual mean limit of 40µg/m^3, which was further revised to 10µg/m^3, as of September 2021 (World Health Organisation, 2021). Any change in weather conditions, traffic or additional sources of NO_2 in close proximity to a location could have led to an exceedance of the previous annual mean limit. Therefore, it was critical to identify mitigation measures which could target pollution sources at these locations to reduce the annual mean measurements. The revision of the WHO annual mean limit to 10µg/m^3 presents a further challenge, as the majority of air quality monitoring stations in Ireland currently exceed this limit, apart from rural monitoring stations. Therefore, wide scale mitigation measures which aim to reduce pollution across large regions would be necessary to comply with the new NO_2 limit. The United Kingdom Government has identified a wide range of measures which are focused on reducing NO_2 throughout towns and cities (Department for Environment Food & Rural Affairs and Department for Transport, 2017). The measures which are currently in place in the UK include:

- Ultra Low Emission Zones (ULEZ) / Low Emission Zones (LEZ): which encourage the use of alternate transport modes and / or upgrading of vehicle fleet to newer standards / Euro Classes
- Investment in the road network: improving the conditions of the existing road network and providing alternate routes to avoid congestion in towns and cities
- Investment in cycling, walking and public transport: providing the network and services for other transport modes will encourage the change from private vehicles
- Retrofitting existing vehicles: promotes the modification of engine technologies within the existing fleet which have significant potential for reducing pollutant emissions
- Investment in other transport infrastructure: improving / expansion of the rail network, improving road traffic network at airports (main source of pollution

around airport) and investment in the reduction of pollution from shipping and aviation

The mitigation measures selected for this analysis would need to be compatible with the WS-LUR model developed in Chapters 3 and 4 and therefore should target one or a number of the variables within the model. Therefore, the objectives of this chapter of the research are to:

- Identify a number of mitigation measures to reduce the NO_2 concentrations at various locations;
- Collect the following data for input to the WS-LUR model to assess the performance of the mitigation measures:
  i. Inverse Distance Weighted Vehicle Kilometres Travelled
  ii. Road Density
  iii. Commercial Properties
  iv. Meteorological Data
  v. Land Use
  vi. Vehicle Fleet Breakdown
- Estimate the changes in NO_2 concentrations due to the implementation of the mitigation measures using the WS-LUR model. The mitigation measures selected for analysis are:
  a. Blanchardstown Business Hub Relocation
  b. SPSV and LPSV Fleet Diesel Removal
  c. Cork Ring Road
  d. Dublin City Low Emission Zone

6.1. Blanchardstown Business Hub Relocation

The COVID analysis completed in Chapter 5 identified significant reductions in NO_2 concentrations throughout Ireland. The main factors in pollution reduction were due to restrictions introduced during this period:

- Restrictions on travel distance resulted in reduced traffic flows across the majority of routes (particularly inter-urban routes);
- Restrictions on businesses resulted in commercial properties closing and implementing a remote working scenario for non-essential businesses (i.e. non-

health, non-grocery, etc.). This significantly reduced the total distance travelled by workers throughout the country.

Based on the pollution reduction achieved during the COVID lockdown period a mitigation measure which would replicate the scenarios above would be successful in significantly reducing pollution across a wide region. The Blanchardstown Business Hub Relocation was identified as a mitigation measure with the aim of relocating trip attractions away from an area experiencing high levels of air pollution. This relocation was expected to have a number of positive effects, such as:

- Reducing trip attractions (businesses) in an area would be expected to reduce the number of people exposed to the high levels of air pollution and also improve traffic in the area, which would result in reductions in NO_2;
- Relocating businesses to another area which has considerably lower levels of traffic and pollution and is more centrally located to the workforce, would be expected to reduce the distance travelled by the population and therefore, would reduce pollution across a wider region.

The changes in NO_2 concentrations at the existing and new business hub locations and at a number of other locations across the Leinster Province were modelled to determine the overall effect of the mitigation measure. Blanchardstown and Kildare Town were selected based on the following Central Statistics Office information on commuting/working population and air quality information provided by the Environmental Protection Agency.

The statistics in Section 2.4.1 highlight the large population that are traveling long distances to work. These statistics reinforce the need to locate future business developments in areas that are more central to the working population, avoiding congestion and increases in air pollution in areas that are currently experiencing relatively poor air quality. This analysis aims to identify the changes in ambient NO_2 due to the relocation of an existing business hub, which would highlight the importance of site selection for future developments and reducing the distance travelled by the large population of commuters identified above. The businesses which were targeted for this mitigation measure were those which were not dependent on the locale to carry out their duties and also were not considered essential services such as health, retail, etc. serving the population of the surrounding area. Further details of these businesses are provided within Section 6.1.1.1 of the thesis.

A number of factors highlighted Blanchardstown as an area which would benefit from the relocation of the business hub. The EPA monitoring station at Blanchardstown continues to record annual average NO_2 concentrations of approximately 30 μg/m^3, which is substantially greater than any other station located outside of the Dublin City Centre area (Environmental Protection Agency, 2012; Environmental Protection Agency, 2013; Environmental Protection Agency, 2014; Environmental Protection Agency, 2015; Environmental Protection Agency, 2016; Environmental Protection Agency, 2017; Environmental Protection Agency, 2018; Environmental Protection Agency, 2019). This annual average concentration is on a par with the worst affected monitoring stations within the city centre region since 2011 (Winetavern Street and Coleraine Street) and is close to the Ambient Air Quality and Clean Air for Europe Directive 2008/50/EC limit of 40 μg/m^3 (European Union, 2008) and exceeds the post-September 2021 WHO limit of 10 μg/m^3 (World Health Organisation, 2021). The Blanchardstown station continues to achieve hourly maximum concentrations in the region of 200 μg/m^3 year-on-year since 2011, which is the hourly limit set in the Ambient Air Quality and Clean Air for Europe Directive 2008/50/EC and should not be exceeded more than 18 times in a calendar year (European Union, 2008). It is also one of the stations with a large number of recordings above the Air Quality Standards Regulations 2011 (S.I. No. 180/2011) Lower Assessment Threshold (LAT) ($>$100 μg/m^3) and Upper Assessment Threshold (UAT) ($>$140 μg/m^3) concentrations (Department of Environment, Heritage and Local Government, 2011). Between 2011 and 2018, the UAT was exceeded 113 times and the LAT was exceeded 1194 times (Environmental Protection Agency, 2012; Environmental Protection Agency, 2013; Environmental Protection Agency, 2014; Environmental Protection Agency, 2015; Environmental Protection Agency, 2016; Environmental Protection Agency, 2017; Environmental Protection Agency, 2018; Environmental Protection Agency, 2019). Relocating businesses from this location will reduce the number of people exposed to high levels of pollution experienced in this area on a daily basis but will also benefit people permanently living in Blanchardstown and the largely residential surrounding area as the traffic in this location would be expected to reduce considerably.

6.1.1. Methodology and Data

Blanchardstown Business Hub was selected as the business hub which was currently located in an area experiencing high levels of NO_2 pollution and Kildare Town was identified as an ideal new location for the business hub based on the statistics introduced in Section 6.1 above. The locations of all EPA monitoring stations located within the confines of the East Region of the NTA model were considered in this analysis. A number of additional locations were included in the analysis as the number of EPA monitoring stations located close to the original and new business locations were limited. Two locations, west (Tyrellstown) and east (Blanchardstown Business Campus) of the Blanchardstown Business Hub were identified as well as three additional locations around Kildare Town, one in the town centre (Saint Brigid's Cathedral / Market Square), one south of the town (south of the M7 motorway Kildare interchange) and another to the west of the town (Kildare Village / south of the M7 motorway Kildare interchange); locations are also identified in Figure 6.1, Figure 6.2, Figure 6.3, Figure 6.4 and Figure 6.5.

The number of public transport options and frequency of services was one of the key factors in the decision for the relocation of the businesses. Any of the working population currently living in Dublin City Centre that use public transport to travel to/from work would be largely unaffected as numerous public transport options are available to travel to Kildare Town. The public transport options servicing the Blanchardstown area are:

- Multiple Bus Éireann routes from Busáras in the city centre to North/East Meath servicing Blanchardstown. Multiple Dublin Bus routes from within the Greater Dublin Area travelling to/through the Blanchardstown area;
- Train services to Castleknock (within 0.5km of Blanchardstown) located on the Sligo - Connolly Station route. Connolly Station is also serviced by the northeast (Belfast/Dundalk) and southeast (Rosslare) train services;
- LUAS red and green lines do not travel directly to Blanchardstown but are interconnected with the train and bus routes described above

There are a number of public transport options for travelling to Kildare Town such as:

- Bus operators and routes that service Kildare Town:
    - GoAhead Commuter service between Dublin City and Rathangan (West Kildare)
    - Dublin Coach services to Ennis/Limerick/Tralee/Killarney and service between Kildare Town and Portarlington
    - Kenneally's Bus services between Limerick and Dublin Airport
    - Kyanitedale Ltd. services between Monasterevin and Sallins/Naas

    - JJ/Bernard Kavanagh services between Carlow and Curragh (East of Newbridge)
    - Dualway Coaches services between Kildare Town and Tallaght
    - Kenneally's Bus services between Maynooth and Portlaoise
- Trains service to Kildare Town:
    - Dublin Heuston to Cork/Tralee route
    - Dublin Heuston to Galway route
    - Dublin Heuston to Waterford route
    - Dublin Heuston to Limerick/Ennis/Nenagh route
    - Dublin Heuston to Westport/Ballina route
    - Grand Canal Dock to Portlaoise route
- LUAS red and green lines do not travel to Kildare but are interconnected with the train and bus routes described above

6.1.1.1. Commercial Properties Data

Commercial properties data was retrieved from the EPA GIS Department and An Post / Geodirectory (GeoDirectory, 2020) in ArcGIS points file format. The data respresented records of all commercial properties as of 2019 within the area covered by the National Transport Authority's East Region Model (National Transport Authority, 2020), which included details such as location and business type.

The National Transport Authority had 4 job attraction categories and each job type was accounted for once in each of the categories. The four job categories were:

1. Health or non-health
2. Food or non-food
3. Retail or non-retail
4. Non-grocery shopping or all jobs excluding non-grocery shopping.

The job attractions defined as non-health, non-food, all jobs excluding non-grocery shopping and non-retail were the focus of this analysis. An example of how the number of non-health job attractions that would not be relocated to Kildare Town were estimated, is provided below in Equation 6.1. This assumption provided a reasonable estimate as to the number of commercial properties which did not match our criteria for relocation as they were considered either retail or health.

$$N_{B,NH} = N_A \, x \, (100\% - (P_{H\&R}) - (P_{H\&NR}) - (P_{NH\&NR}))$$ **Eqn. 6.1: Number of Non-Health Job Attractions to Stay in Blanchardstown**

Where:

$N_{B,NH}$ = Total Number of Non-Health Job Attractions to Stay in Blanchardstown

N_A = Total Number of Job Attractions before Relocation

$P_{H\&R}$ = % Total Job Att. Categorised as Health and Retail

= (Health Job Att./All Job Att.) x (Retail Job Att./All Job Att.)

$P_{H\&NR}$ = % Total Job Att. Categorised as Health and Non-Retail

= (Health Job Att./All Job Att.) x (Non-Retail Job Att./All Job Att.)

$P_{NH\&NR}$ = % Total Job Att. Categorised as Non-Health and Non-Retail

= (Non-Health Job Att./All Job Att.) x (Non-Retail Job Att./All Job Att.)

Similarly, Equation 6.2 was used to estimate the number of non-retail job attractions which would not be relocated to Kildare Town as they were also categorised as health.

$$N_{B,NR} = N_A \, x \, (100\% - (P_{H\&R}) - (P_{NH\&R}) - (P_{NH\&NR}))$$ **Eqn. 6.2: Number of Non-Retail Job Attractions to Stay in Blanchardstown**

Where:

$N_{B,NR}$ = Total Number of Non-Health Job Attractions to Stay in Blanchardstown

$P_{NH\&R}$ = % Total Job Att Categorised as Non-Health and Retail

= (Non-Health Job Att./All Job Att.) x (Retail Job Att./All Job Att.)

The third level education attractions in the Blanchardstown Business Hub region were also identified for relocation to Kildare Town as a number of the businesses could be dependent on the third level institution for future employees and summer work placements as part of course programmes. The total number of job attractions identified for relocation was then equally split between the 3 Central Statistics Office Small Areas which covered Kildare Town and surrounding areas.

Table 6.1 shows the number of commercial properties within a 1km radius of the modelled locations for the pre- and post-mitigation measure scenarios considered in this analysis. The commercial properties data was analysed so that the number of businesses within the Central Statistics Office Small Areas covering the Blanchardstown Business Hub region reflects the reductions in commercial properties in that area after the Hub was relocated. The data was also used to reflect the increase in the number of businesses in the Central Statistics Office Small Areas covering the Kildare Town region by the same amount, after hub relocation. The businesses which matched the description used by the National Transport Authority in their transport modelling (i.e. businesses defined as non-health, jobs excluding non-grocery shoppoing, non-retail and non-food) were selected from the Geodirectory database to form the commercial properties data which was input into the enhanced WS-LUR model. Examples of the commercial property types that were targetted in the Geodirectory database for this mitigation measure include a number of business classes within the information / communication, finanacial / insurance, professional / scientific / technical activites and administrative / support service activities divisions, as categorised by the NACE codes (Eurostat, 2008).

The traffic modelling within the NTA model relocated trip attractions from Central Statistics Office Small Areas covering the Blanchardstown business hub to the Kildare Town Central Statistics Office Small Areas. The traffic modelling therefore assumed the attractions were spread evenly across the entirety of the small areas and not located at a specific point. Therefore, the same approach was taken when determining the new commercial properties numbers within each of the wind directional sectors for the stations located near the Kildare Town Central Statistics Office Small Areas to retain the link with the traffic flows produced by the traffic modelling.

Table 6.1: Commercial Properties by Directional Sector for Blanchardstown Business Hub Relocation

EPA Monitoring Station		N	NE	E	SE	S	SW	W	NW
Ballyfermot		94	44	16	87	61	29	16	112
Blanchardstown	Pre-	30	1	2	34	8	28	204	24
	Post-	29	1	2	34	8	27	160	24
Blanchardstown Business Campus		97	64	86	93	76	19	9	204
Celbridge		24	163	93	0	6	10	1	4
Coleraine Street		224	1057	1499	2391	857	1225	481	32
Davitt Road		115	60	128	41	66	19	216	128
Dún Laoghaire		623	43	155	49	34	74	33	302
Emo Court		1	0	0	1	0	0	0	2
Kildare Village	Pre-	65	222	36	17	15	19	0	12
	Post-	65	222	36	24	22	26	0	12
Kilkitt		5	2	2	1	1	1	0	1
Knocklyon		5	9	7	7	25	4	8	29
M7 Junction South	Pre-	36	70	4	4	0	4	0	0
	Post-	43	77	11	11	7	11	7	7
Navan		40	22	633	154	61	27	4	14
Newbridge		364	2	1	5	0	37	30	174
Pearse Street		869	687	871	706	1589	906	1765	1183
Portlaoise		8	11	17	7	97	236	312	12
Rathmines		424	321	195	110	88	62	156	91
Ringsend		7	6	26	6	54	49	125	5
St Brigid’s Cathedral/ Market Square		16	58	14	47	100	176	5	5
Seville Lodge		3	25	2	5	3	16	26	1
St Anne’s Park		94	57	34	19	13	1	5	24
St. John’s Road		63	183	359	559	175	221	62	11
Swords		13	38	100	110	328	19	12	15
Tyrrelstown		90	6	1	41	11	2	1	0
Winetavern Street		968	2090	2449	1351	674	1110	524	1254

6.1.1.2. Inverse Distance Weighted Vehicle Kilometres Travelled Data

In this section the steps taken to determine the IDWVKT within each of the directional sectors at all modelled locations are described and details of the data sources are provided. The changes in flows from the pre- and post-mitigation measure scenarios for each vehicle type and AADT across all routes are mapped to determine the locations which contribute to changes in IDWVKT. The methodology used to analyse the data was the same as that used for the IDWVKT data in the WS-LUR model development, described in Section 3.3.4.

Traffic flow data for the Blanchardstown business hub relocation scenario was based on modelled flow outputs from the National Transport Authority's East Region Model (National Transport Authority, 2020) which includes routes of all standards (motorway, national, rural, local, unclassified routes) within Leinster and parts of Ulster. This analysis focused on relocating business types which were not dependent on the locale or were not businesses that provided key services to the public such as groceries, health, retail and food facilities.

The resultant change in traffic was captured by traffic modelling carried out by the National Transport Authority using their National Transport Model (National Transport Authority, 2021). They relocated attractions within the model from the Central Statistics Office Small Areas covering the Blanchardstown Business Hub region to the Central Statistics Office Small Areas covering the Kildare Town region, which would in effect change the flows on routes due to the change in the origin / destination of journies to / from the attractions.

Figure 6.1, Figure 6.2, Figure 6.3, Figure 6.4 and Figure 6.5 show the flow changes in each of the vehicle type categories (AADT, Car / Taxi, LGV, HGV and LPSV) for every route in the NTA east region model due to the relocation of businesses from the Blanchardstown business hub to Kildare Town and its surrounds. These locations were identified as areas where considerable traffic flow changes could occur and would be in close proximity to the original and new business locations. The analysis quantified the changes in ambient NO_2 concentrations changes at these key locations.

Overall, the relocation had a positive influence on vehicle flows on the major (national and motorway) routes into Dublin, with reductions of up to 10% in AADT on the majority of route sections, as shown in Figure 6.1. The M1/N1 route between Belfast and Dublin, M3/N3 route between Cavan and Dublin, M4/N4 route between Sligo / Galway and

Dublin, M7/N7 route between Kildare and Dublin and M9 route between Waterford and east of Kildare Town experienced reductions in the range of 1 – 10% in car / taxi flows, more than 10% reductions in LGVs and reductions of greater than 100 vehicles in the HGVs and LPSVs categories as shown in Figure 6.2, Figure 6.3, Figure 6.4 and Figure 6.5. Reductions in car / taxi flows in the range of 1 - 10% were observed on the majority of routes, as shown in Figure 6.2. As expected, due to the increased job attractions within the Kildare Town region, flows on routes towards the town increased by more than 10% for the AADT, Car / Taxi and LGV vehicle categories and the number of HGVs and LPSVs towards Kildare Town also increased by more than 100 vehicles per day.

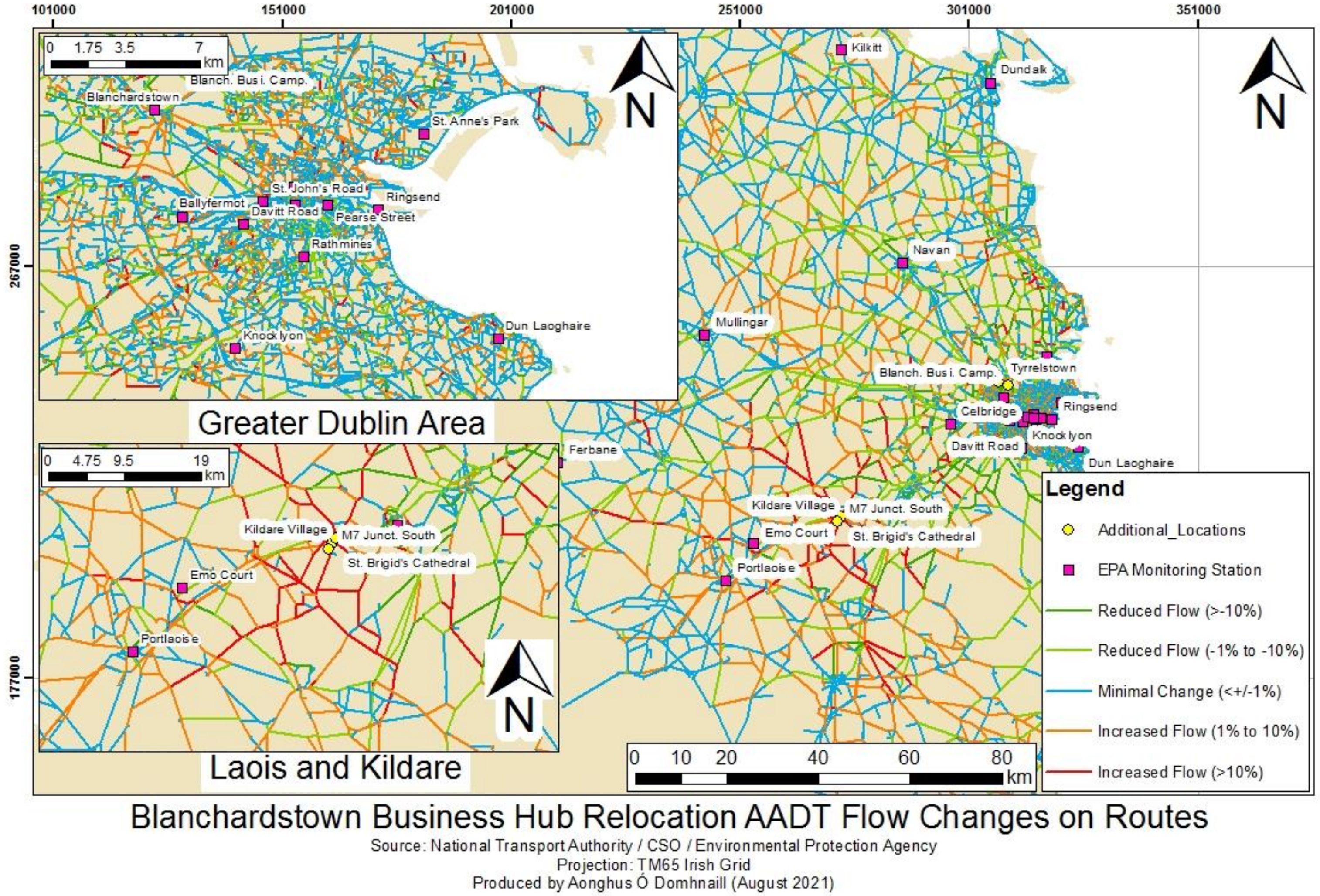


Figure 6.1: Blanchardstown Business Hub Relocation AADT Flow Changes on Routes

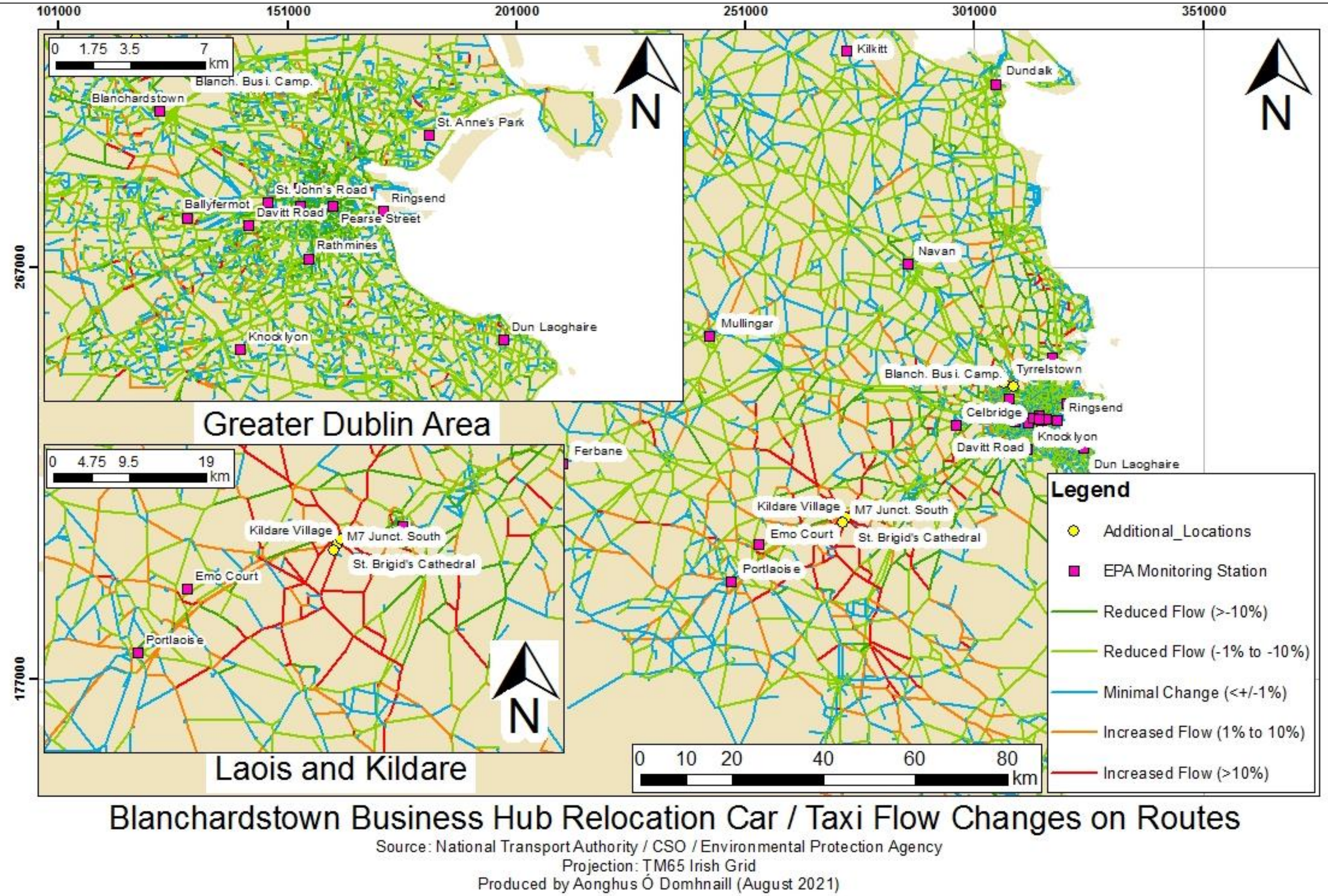


Figure 6.2: Blanchardstown Business Hub Relocation Car / Taxi Flow Changes on Routes

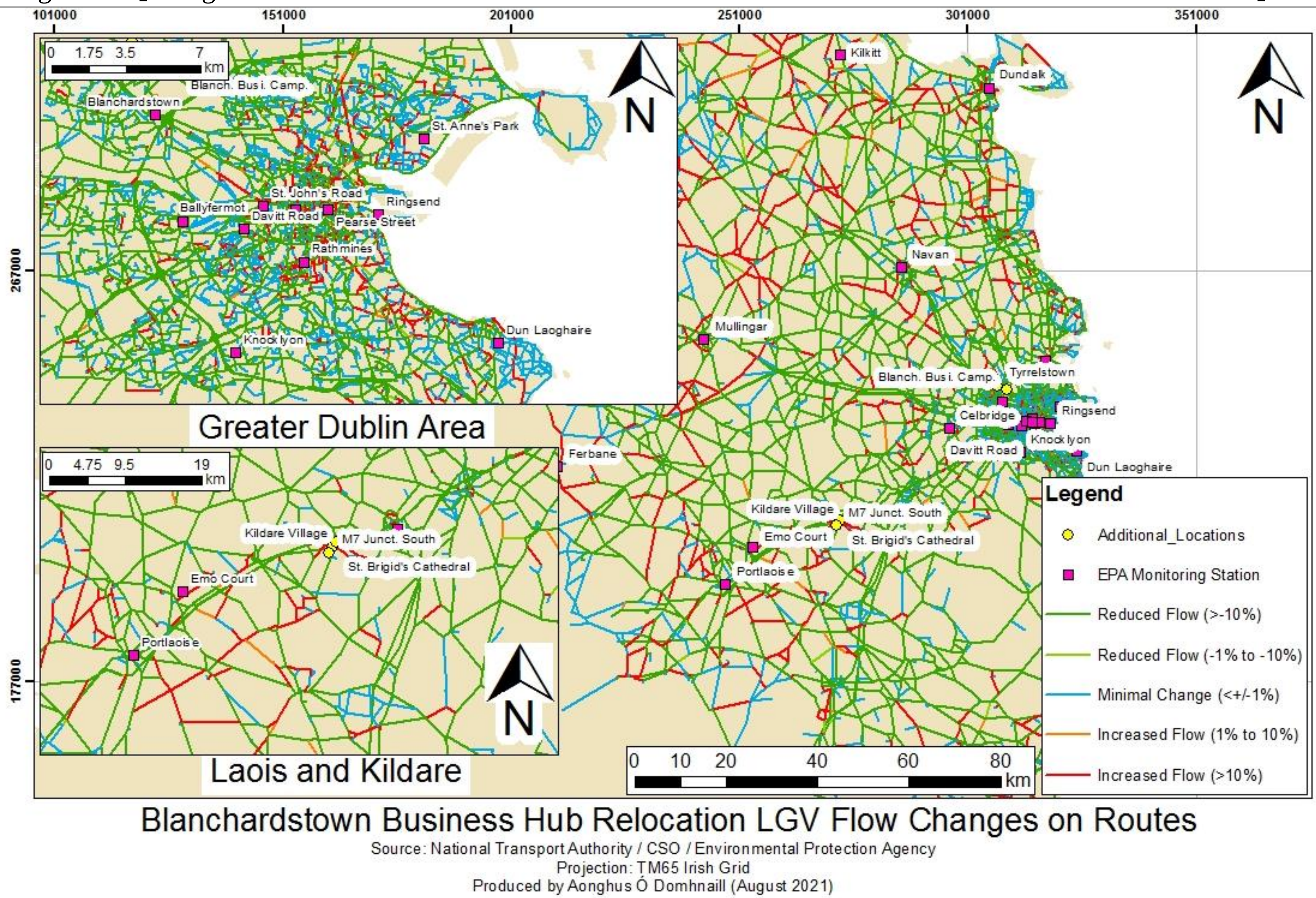


Figure 6.3: Blanchardstown Business Hub Relocation LGV Flow Changes on Routes

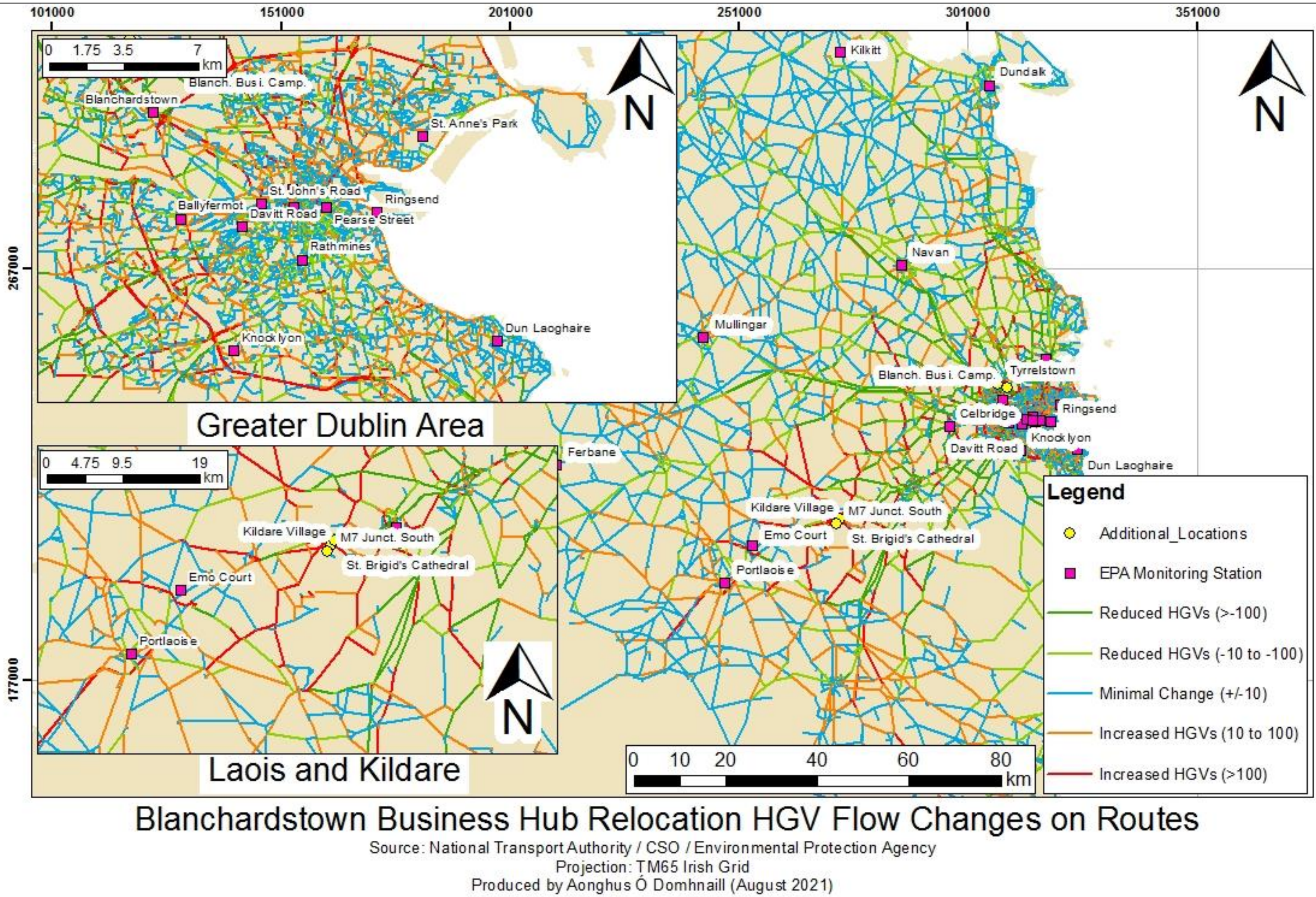


Figure 6.4: Blanchardstown Business Hub Relocation HGV Flow Changes on Routes

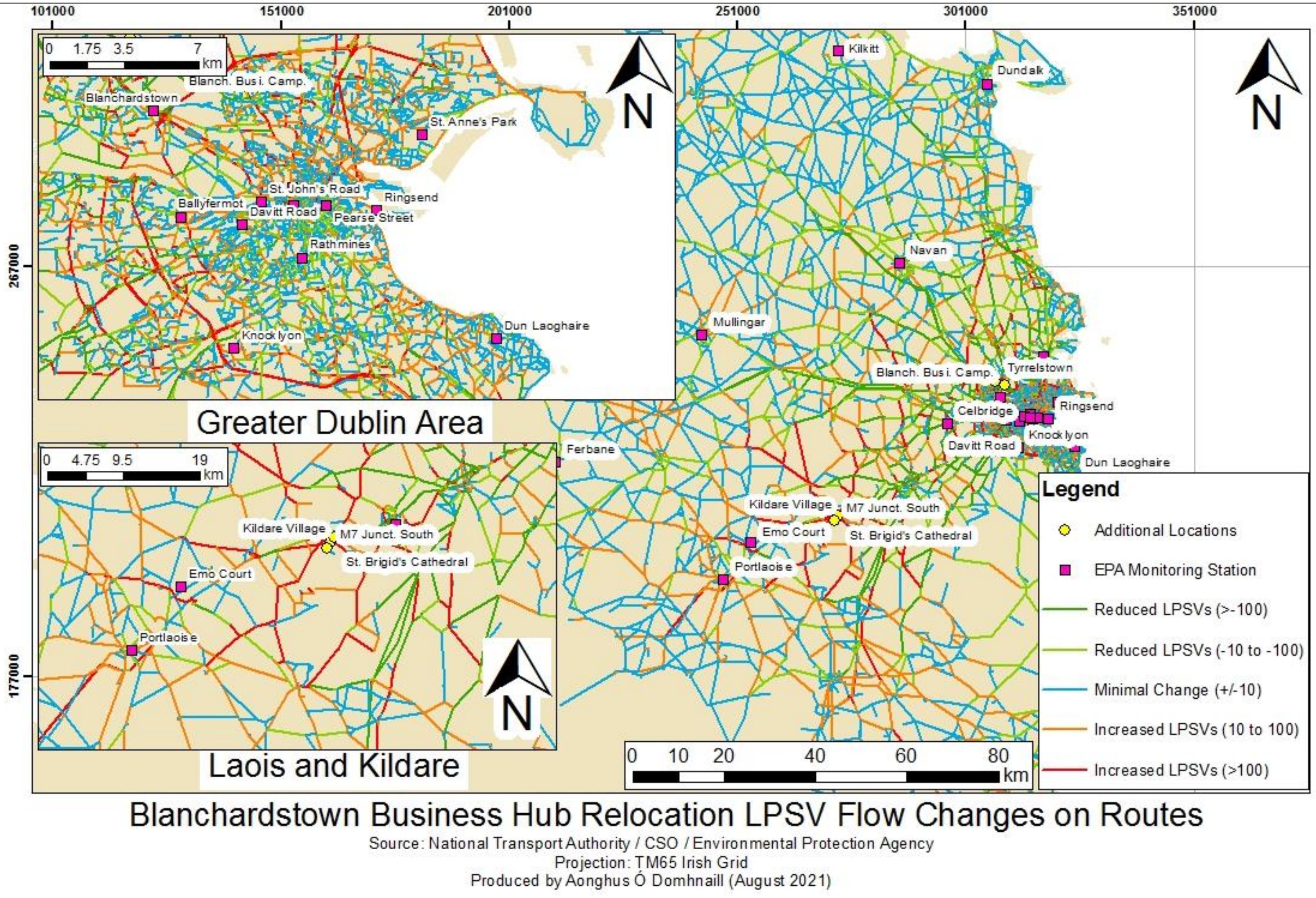


Figure 6.5: Blanchardstown Business Hub Relocation LPSV Flow Changes on Routes

Table 6.2 shows the Inverse Distance Weighted Vehicle Kilometres Travelled (IDWVKT) for all directional sectors at all modelled locations (locations mapped in Figure 6.1, Figure 6.2, Figure 6.3, Figure 6.4 and Figure 6.5 above). The IDWVKT reduced in the majority of directional sectors for all modelled locations outside of Kildare Town. The IDWVKT increased in 4 to 5 directional sectors for modelled locations in close proximity to Kildare Town. Apart from two minor increases in the south-west sectors for two locations (M7 Kildare Junction South and St. Brigid's Cathedral), none of the other increases occurred in the predominant wind direction sectors (West and South-West). Changes within the predominant wind directional sectors are weighted more heavily than other sectors using the Wf_i factor in the WS-LUR equation (Equations 3.1 and 3.2) and therefore the changes described above would not have as significant an impact on the modelled ambient NO_2 concentrations at these locations.

A substantial change in vehicle kilometres travelled was noticed at the St. John's Road location with a ~ 210 000 km reduction in the north-east sector whilst the south sector increased by 190 000 km (see Table 6.2). This change would be expected as traffic leaving the city centre originally for Blanchardstown, that would travel north east of the St. John's Road monitoring station, would instead travel along routes which are 0.3 to 3 km south of the monitoring station towards the M7 / N7 route to Kildare after the hub relocation. The Davitt Road station experienced an increase in the IDWVKT for the west sector which is mainly related to the increase in traffic on the section of the M50 between the M4 and M7 junctions but also on a number of regional routes west of Davitt Road travelling towards the M7 / N7 junction on the M50. The Dun Laoghaire monitoring station experienced higher IDWVKT in the south-west sector due to an increase in traffic flows on a number of routes towards the M50 as well as an increase in traffic on the M50 motorway. In the original case, the toll on the M50 between the M4 and Blanchardstown junctions may deter cars from travelling to Blanchardstown.

Table 6.2: Inverse Distance Weighted Vehicle Kilometres Travelled by Directional Sector for 2019 and 2019 Blanchardstown Business Hub Relocation Scenarios

		INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED							
EPA Monitoring Station	**Scenario**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot, Dublin	2019	194 768	161 553	188 732	145 847	263 197	216 931	416 008	306 598
	2019 Blanch. Business Hub Relo.	178 468	143 871	170 698	131 643	228 841	187 461	367 073	273 172
Blanchardstown, Dublin	2019	77 790	236 696	439 530	345 875	396 828	208 504	97 705	482 825
	2019 Blanch. Business Hub Relo.	56 219	223 675	516 833	227 914	357 945	187 409	79 598	417 922
Blanch. Business Campus	2019	54 531	57 019	186 471	333 991	270 017	151 507	104 531	45 195
	2019 Blanch. Business Hub Relo.	45 184	49 272	168 583	301 441	244 353	131 962	87 723	33 102
Celbridge, Kildare	2019	117 837	87 257	171 818	29 621	12 755	5 107	30 940	33 278
	2019 Blanch. Business Hub Relo.	106 974	79 253	46 351	122 389	18 352	4 452	26 084	29 501
Coleraine Street, Dublin	2019	162 434	240 294	208 940	260 007	275 536	277 578	173 414	121 639
	2019 Blanch. Business Hub Relo.	181 146	228 609	182 258	254 540	253 009	278 077	111 371	109 456
Davitt Road, Dublin	2019	171 050	253 387	252 913	126 347	126 989	301 517	394 107	155 163
	2019 Blanch. Business Hub Relo.	144 403	240 346	239 937	112 079	110 550	272 133	621 507	139 882
Dún Laoghaire, Dublin	2019	16 682	5 914	8 623	9 422	116 102	174 304	116 111	60 485
	2019 Blanch. Business Hub Relo.	12 532	3 764	8 133	9 019	108 436	206 555	105 958	54 009
Emo Court, Laois	2019	9 575	2 423	6 579	11 143	57 071	14 051	8 181	175
	2019 Blanch. Business Hub Relo.	8 506	2 350	6 341	10 442	53 036	13 179	7 837	167
Kildare Village, Kildare	2019	19 851	30 550	99 107	19 054	35 543	236 262	106 644	18 574
	2019 Blanch. Business Hub Relo.	21 655	35 965	89 272	22 210	58 672	172 048	94 865	17 722

INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED

EPA Monitoring Station	Scenario	N	NE	E	SE	S	SW	W	NW
Kilkitt, Monaghan	2019	3 127	865	737	846	1 416	2 607	239	3 265
	2019 Blanch. Business Hub Relo.	2 854	860	711	791	1 376	2 487	240	3 168
Knocklyon, Dublin	2019	137 876	123 269	102 029	169 817	74 153	169 440	217 199	329 821
	2019 Blanch. Business Hub Relo.	122 685	106 064	95 525	151 359	52 531	151 934	194 308	295 236
M7 Kildare Junction South	2019	58 762	60 648	103 746	51	7 573	818	80 740	9 904
	2019 Blanch. Business Hub Relo.	26 555	92 022	107 207	0*	13 783	1 313	74 041	10 607
Navan, Meath	2019	21 784	79 470	80 166	51 128	55 467	26 890	28 630	53 425
	2019 Blanch. Business Hub Relo.	16 522	78 344	67 018	51 686	52 042	24 571	25 151	49 385
Newbridge, Kildare	2019	33 724	69 436	32 052	329 566	6 763	26 971	29 994	26 801
	2019 Blanch. Business Hub Relo.	28 546	63 813	29 348	288 744	6 653	25 102	27 930	24 058
Pearse Street, Dublin	2019	285 306	217 652	124 010	160 562	212 096	203 181	267 116	314 616
	2019 Blanch. Business Hub Relo.	271 633	211 188	118 469	151 309	203 126	186 234	253 979	302 366
Portlaoise, Laois	2019	4 717	152 320	23 860	121 565	19 703	38 123	49 847	19 311
	2019 Blanch. Business Hub Relo.	4 792	132 681	21 184	112 194	18 142	35 184	44 198	17 734
Rathmines, Dublin	2019	285 126	194 927	155 137	136 245	114 889	143 960	132 718	174 800
	2019 Blanch. Business Hub Relo.	271 943	178 575	146 591	110 522	123 769	127 199	116 776	161 983
Ringsend, Dublin	2019	115 356	18 791	11 825	19 563	163 191	167 176	255 054	232 397
	2019 Blanch. Business Hub Relo.	108 090	17 015	6 788	17 337	142 682	157 948	244 558	222 115
St. Brigid’s Cathedral	2019	11 425	21 010	101 445	10 609	28 000	88 208	99 003	24 068
	2019 Blanch. Business Hub Relo.	12 756	30 070	91 427	7 108	51 619	89 222	91 867	15 737

INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED

EPA Monitoring Station	Scenario	N	NE	E	SE	S	SW	W	NW
Seville Lodge, Kilkenny	2019	334	3 004	5	0*	0*	0*	0*	0*
	2019 Blanch. Business Hub Relo.	292	2 627	4	0*	0*	0*	0*	0*
St Anne's Park, Dublin	2019	111 881	65 595	15 942	7 134	11 205	91 542	169 472	140 068
	2019 Blanch. Business Hub Relo.	102 704	61 149	14 213	6 470	10 235	86 964	162 034	120 808
St. John's Road, Dublin	2019	140 106	398 692	372 956	185 819	155 607	164 858	421 177	102 699
	2019 Blanch. Business Hub Relo.	135 072	183 611	349 126	175 264	348 653	146 687	255 130	95 256
Swords, Dublin	2019	11 444	120 126	55 381	286 570	259 513	52 740	22 701	54 117
	2019 Blanch. Business Hub Relo.	9 673	107 042	48 250	273 690	216 260	46 853	20 808	47 394
Tyrrelstown, Dublin	2019	15 620	92 820	86 837	248 605	208 391	133 386	90 332	14 569
	2019 Blanch. Business Hub Relo.	10 717	81 537	82 840	207 518	174 987	127 061	76 174	13 252
Winetavern Street, Dublin	2019	221 971	334 984	207 967	242 724	237 848	196 574	261 188	219 727
	2019 Blanch. Business Hub Relo.	241 034	289 221	202 567	222 771	226 073	165 440	250 249	197 417

* No traffic flow data within directional sector

6.1.1.3. Vehicle Fleet Data

In this section the steps taken to determine the vehicle fleet breakdown are described and details of the data source are provided. The Irish Bulletin of Vehicle and Driver Statistics report published by the Department of Transport, Tourism and Sport was used to determine the vehicle fleet for 2019 (Department of Transport, Tourism and Sport, 2020). Details of the fuel type, unladen weights, engine capacities and year when first licensed were available in the Irish Bulletin of Vehicle and Driver Statistics to determine the Euro Class breakdown of each vehicle category (i.e. Passenger Cars (PCs), Light Commercial Vehicles (LCVs), Heavy Duty Vehicles (HDVs), etc.). These details were then used to determine the NO_2 emission weighting for each vehicle type in 2019, using the process shown in the flow chart in Figure 6.6, beginning with the vehicle type breakdown which is presented in Table 6.3. The vehicle fleet breakdown described below was used for all of the other mitigation measure scenarios described in this chapter, apart from the post-mitigation scenario for the public service vehicle diesel removal, which is described in Section 6.2.

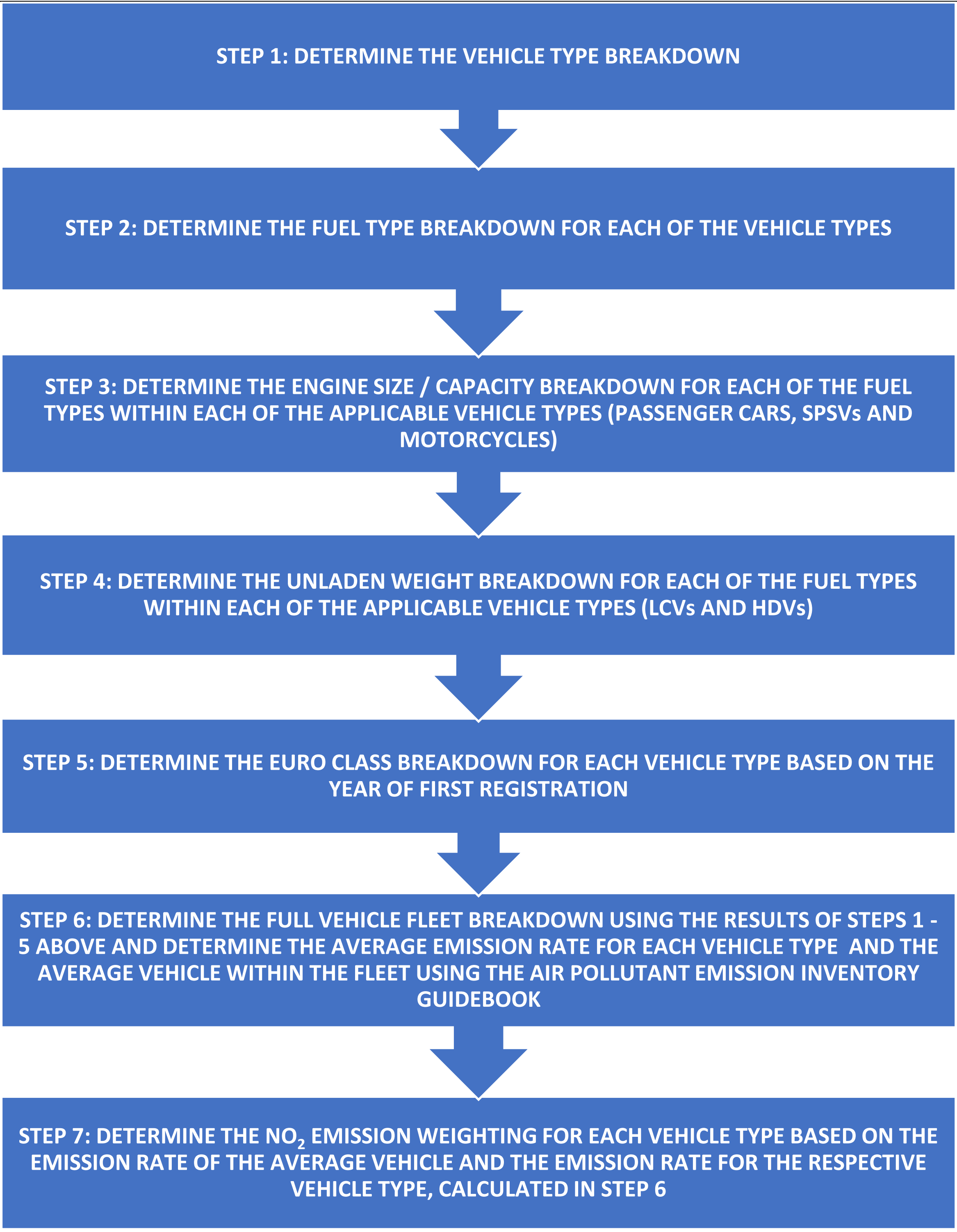


Figure 6.6: Vehicle Fleet Breakdown and NO_2 Emission Weighting Process

Table 6.3: Vehicle Type Breakdown

Vehicle Type	Percentage of Overall Vehicle Fleet
Passenger Car (PC)	77.47%
Light Commercial Vehicle (LCV)	11.68%
Heavy Duty Vehicle (HDV)	1.39%
Small Public Service Vehicles (SPSV)	0.77%
Large Public Service Vehicle (LPSV)	0.41%
Motorcycle (M)	1.51%

Table 6.4 shows the fuel type breakdown for all vehicle types as of 2019. Diesel was the pre-dominant fuel type for passenger cars, LCVs, HDVs, SPSVs and LPSVs at 57%, 99.7%, 99.7%, 82% and 99.9% respectively. Petrol was the most common fuel type in the motorcycle fleet at 99.6%, the second most common fuel type in the passenger car fleet at 40% and the third most common fuel type in the SPSVs at 7%. Hybrid petrol was the third most common fuel type in passenger cars at 2% and the second most common fuel type in the SPSVs fleet at 11%.

Table 6.4: Fuel Type Breakdown by Vehicle Type

Fuel Type	PC	LCV	HDV	SPSV	LPSV	M
Petrol	40.03%	0.17%	0.17%	6.57%	-	99.62%
Diesel	56.83%	99.66%	99.66%	81.97%	99.93%	-
Electric	0.39%	0.12%	0.12%	0.28%	-	0.17%
Hybrid Petrol	2.32%	-	-	10.97%	-	-
Ethanol	0.38%	-	-	0.02%	-	-
CNG	0.00%	-	-	0.00%	0.00%	-
LPG	0.00%	-	-	0.00%	-	-

Table 6.5 defines the engine capacity range of each of the engine sizes for the petrol, diesel and hybrid petrol fuel types in the passenger car and small public service vehicle fleets. Table 6.6 identifies the percentage breakdown for each engine size in the petrol, diesel and hybrid petrol fuel types in the passenger cars and small public service vehicles. The small engine size, which represents vehicles with engine capacities between 1 000 and 2 000 cubic centimetres, was the most common size in all fuel types. The mini engine capacity size made up 8% of petrol vehicles, whilst 6% of diesel and hybrid petrol vehicles and 5% of petrol vehicles were in the medium engine capacity range. Only 0.3% of petrol and 0.3% of diesel and hybrid petrol vehicles were in the large engine capacity range.

Table 6.5: Fuel Type / Engine Size Capacity Definitions

Fuel Type / Engine Size	Engine Capacity
Petrol Mini	≤1 000 cubic centimetres (c.c.)
Petrol Small	1 000 – 2 000 c.c.
Petrol Medium	2 000 – 3 000 c.c.
Petrol Large	≥3 000 c.c.
Diesel Small	≤2 000 c.c.
Diesel Medium	2 000 – 3 000 c.c.
Diesel Large	≥3 000 c.c.
Hybrid Petrol Small	≤2 000 c.c.
Hybrid Petrol Medium	2 000 – 3 000 c.c.
Hybrid Petrol Large	≥3 000 c.c.

Table 6.6: Passenger Cars and SPSVs Engine Size Breakdown

Engine Size	Petrol	Diesel and Hybrid Petrol
Mini	7.95%	-
Small	86.32%	93.78%
Medium	5.46%	5.93%
Large	0.27%	0.29%

Table 6.7 identifies the combined breakdown by fuel type and engine size for the passenger car fleet. Over half (53%) of the entire fleet were powered by small diesel engines and just over a third (35%) of all vehicles were powered by small petrol engines. The most common engine / fuel type combinations outside of these two main types were diesel medium, petrol mini and petrol medium at 3 %, 3% and 2% respectively.

Table 6.7: Passenger Car Full Fuel Type Engine Size Breakdown

Fuel Type	Engine Size	Fuel Type Percentage	Engine Size Percentage	Total Percentage
Petrol	Mini	40.03%	7.95%	3.18%
	Small		86.32%	34.55%
	Medium		5.46%	2.19%
	Large		0.27%	0.11%
Diesel	Small	56.83%	93.78%	53.30%
	Medium		5.93%	3.37%
	Large		0.29%	0.16%
LPG	All Sizes	0.00%	100%	0.00%
Hybrid Petrol	Small	2.32%	93.78%	2.18%
	Medium		5.93%	0.14%
	Large		0.29%	0.01%
Ethanol E85	All Sizes	0.38%	100%	0.38%
Electric	All Sizes	0.39%	100%	0.39%

Table 6.8 identifies the combined breakdown by fuel type and engine size for the small public service vehicle fleet. Small diesel engines were the most common power source at 77% with hybrid petrol small, petrol small and diesel medium ranked second (10%), third (6%) and fourth (5%) most common respectively.

Table 6.8: SPSV Full Fuel Type Engine Size Breakdown

Fuel Type	Engine Size	Fuel Type Percentage	Engine Size Percentage	Total Percentage
Petrol	Mini	6.57%	-	-
	Small		93.78%	6.16%
	Medium		5.93%	0.39%
	Large		0.29%	0.02%
Diesel	Small	81.97%	93.78%	76.87%
	Medium		5.93%	4.86%
	Large		0.29%	0.24%
LPG	All Sizes	0.00%	100%	0.00%
Hybrid Petrol	Small	10.97%	93.78%	10.29%
	Medium		5.93%	0.65%
	Large		0.29%	0.03%
Ethanol E85	All Sizes	0.02%	100%	0.02%
Electric	All Sizes	0.28%	100%	0.28%

Table 6.9 shows the unladen weight breakdown for the goods vehicles (LGVs and HDVs) fleet in Ireland as of 2019. The majority (89%) of goods vehicles had an unladen weight less than 3.5 tonnes with a further 3% within the 3.5 and 7.5 tonne range. Another 6% were within the 7.5 and 15 tonne range whilst only 2% had an unladen weight in excess of 15 tonnes.

Table 6.9: Goods Vehicles Unladen Weight Breakdown

HDV Unladen Weight	Percentage of HDV
<3.5 tonnes	89.37%
3.5 – 7.5 tonnes	2.64%
7.5 – 15 tonnes	6.47%
>15 tonnes	1.52%

Table 6.10 identifies the breakdown by engine capacity for all motorcycles and mopeds as of 2019. Over 81% of all motorcycles had an engine capacity in excess of 250 cubic centimetres (c.c.) and over 95% of mopeds had an engine capacity greater than 50c.c. Only 5% of mopeds were less than 50c.c. whilst 14% of motorcycles were less than 250c.c.

Table 6.10: Motorcycle and Moped Engine Capacity Breakdown

Engine Capacity	Percentage
<50 c.c. Moped	4.66%
>50 c.c. Moped	95.34%
<250 c.c. Motorcycle	14.09%
>250 c.c. Motorcycle	81.25%

The year of registration was then analysed to determine the Euro Classification breakdown within each fuel type / engine size / unladen weight / engine capacity of every vehicle type. Table 6.11 and Table 6.12 identify the Euro Class breakdown within each fuel type / engine size combination for both passenger cars and small public service vehicles. The most common Euro Class in the passenger cars fleet for all engine sizes and fuel types was the Euro 5 Class with Euro 4 the second most common. Over 20% of cars within each of the engine size / fuel types were categorised as one of the Euro 6 Classes with the majority of these in the newer Euro 6 (2017 – 2019) Class. The smaller percentage of vehicles classed as Euro 6 (≤2017) may be due to the introduction of the newer Euro 6 (2017 – 2019) Class within a year and a half of introducing the Euro 6 (≤2017) Class.

Table 6.11: Passenger Car Euro Class Breakdown

Euro Class	Petrol Mini	Petrol Small, Medium and Large	Diesel Small	Diesel Medium and Large	Ethanol and CNG	LPG
Pre-Euro	-	10.00%	-	4.44%	-	4.44%
Euro 1	-	1.7%	-	4.44%	-	4.44%
Euro 2	-	1.7%	-	4.44%	-	4.44%
Euro 3	-	16.97%	-	16.97%	-	16.97%
Euro 4	34.13%	23.79%	34.13%	23.79%	34.13%	23.79%
Euro 5	36.27%	25.28%	36.27%	25.28%	36.27%	25.28%
Euro 6	-	-	-	-	29.60%	20.63%
Euro 6 (≤2016)	9.84%	6.86%	9.84%	6.86%	-	-
Euro 6 (2017 – 2019)	19.76%	13.78%	19.76%	13.78%	-	-
Euro 6 (2020+)	-	-	-	-	-	-

Table 6.12: Small Public Service Vehicles Euro Class Breakdown

Euro Class	Petrol Mini	Petrol Small, Medium and Large	Diesel Small	Diesel Medium and Large
Pre-Euro	-	-	-	-
Euro 1	-	-	-	-
Euro 2	-	-	-	-
Euro 3	-	12.23%	-	12.24%
Euro 4	-	29.95%	34.13%	29.95%
Euro 5	-	31.83%	36.27%	31.83%
Euro 6 (≤2016)	-	8.64%	9.84%	8.64%
Euro 6 (2017 – 2019)	-	17.34%	19.76%	17.34%
Euro 6 (2020+)	-	-	-	-

Table 6.13 shows the Euro Class breakdown for the light commercial vehicles fleet. 14% of LCVs were Euro 6 (2018 – 2020) whilst only 9% of LCVs were Euro 6 (≤2017). Euro 5 accounted for 27% of LCVs whilst 26% and 15% of LCVs were Euro 4 and Euro 3 respectively. A combined 9% of LCVs were Euro 2 Class or lower.

Table 6.13: Light Commercial Vehicles Euro Class Breakdown

Euro Class	Percentage
Pre-Euro	3.08%
Euro 1	3.08%
Euro 2	3.08%
Euro 3	15.22%
Euro 4	26.33%
Euro 5	26.88%
Euro 6 (≤2017)	8.73%
Euro 6 (2018 – 2020)	13.56%

Table 6.14 identifies the Euro Class breakdown for the diesel fuelled HDVs as of 2019. The majority of HDVs were classified as Euro IV or newer with Euro VI the most common class at 47% of diesel HDVs, Euro IV the second most common class at 20% of diesel HDVs and Euro V the third most common class at 20% of diesel HDVs. Higher percentages of vehicles within the newer Euro Classes (Euro IV, Euro V and Euro VI) for HDVs in comparison to the passenger cars, small public service vehicles and LCVs would be expected as the last updates in HDVs occurred in 2008 and 2013 for Euro V an Euro VI respectively, whilst in the same time period four updates were introduced for passenger cars / small public service vehicles and three updates were introduced for LCVs.

Table 6.14: Heavy Duty Vehicles Diesel Euro Class Breakdown

Euro Class	Percentage
Pre-Euro	2.98%
Euro I	2.98%
Euro II	2.98%
Euro III	3.54%
Euro IV	20.17%
Euro V	20.09%
Euro VI	47.23%

Table 6.15 shows the Euro Class breakdown for all LPSVs. Similar to the HDVs the majority of vehicles were classified as one of the newer Euro Classes (Euro IV, Euro V or Euro VI) due to the limited number of updates to the Euro Classes, with the last update introduced in 2013. The Euro VI was the most common class at 47% with the Euro IV the second most common classification in the LPSVs fleet at 20% and the Euro V Class, the third most common at 20%.

Table 6.15: Large Public Service Vehicles Euro Class Breakdown

Euro Class	Percentage
Pre-Euro	3.09%
Euro I	3.09%
Euro II	3.09%
Euro III	3.52%
Euro IV	20.11%
Euro V	20.03%
Euro VI	47.08%

Table 6.16 shows the Euro Class breakdown for all engine capacity ranges for the motorcycle fleet. The European Environmental Agency Air Pollutant Emissions Inventory Guidebook groups all motorcycles that are Euro III or newer into one group (European Environment Agency, 2019). Therefore, for this analysis all motorcycles Euro III or newer were considered Euro III, which was introduced in 2007. Similar to the HDVs and LPSVs, due to the substantial time period since the last major update, a large proportion of vehicles within each of the engine capacity ranges are classified as a newer Euro Class. The percentage of mopeds with engine capacities less than 50 c.c., which were also classified as Euro III, was 76%. Euro III was the most common class for motorcycles also, accounting for 76% of motorcycles. Euro II classification accounted for 18% and 12% of mopeds and motorcycles respectively.

Table 6.16: Motorcycles Euro Class Breakdown

Euro Class	<50c.c. Mop.	All Other Engine Capacities Motorcycles
Pre-Euro	2.97%	6.16%
Euro I	2.97%	6.16%
Euro II	18.04%	11.69%
Euro III	76.02%	76.00%

The vehicle fleet breakdown was determined based on the statistics presented in Table 6.3 to Table 6.16 above and the resultant NO_2 emission weightings which were calculated for each of the vehicle types using Section D3 of the model are shown in Table 6.17.

Table 6.17: Vehicle Type NO_2 Emission Weighting

Vehicle Type	2019 NO_2 Emission Weighting
Passenger Cars	0.828
LGVs	2.138
HGVs	1.436
SPSVs	1.163
LPSVs	2.664
Motorcycles	0.052

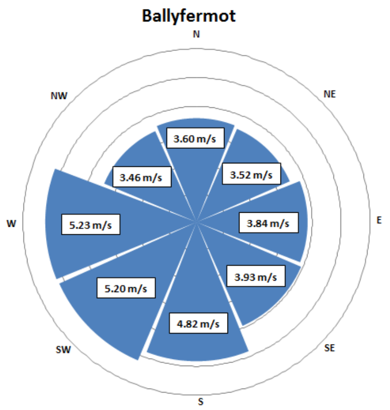
6.1.1.4. Meteorological, Road Density and Land Use Data

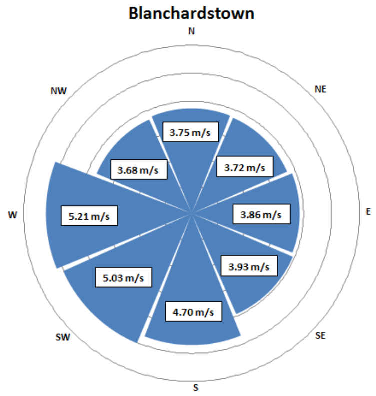
This section introduces the sources of data for the variables which were unaffected by the mitigation measure (meteorological, road density and land use) and therefore values were constant for both the pre- and post-mitigation measure scenarios. The methodology used to analyse the data was the same as that used to develop the background data for the WS-LUR model described in Chapter 3.

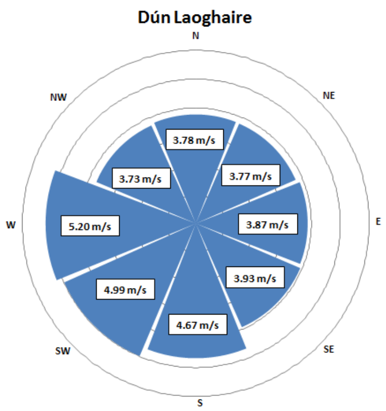
The meteorological data used in this analysis was obtained from the Met Éireann historical database and included data for all monitoring stations including offshore stations (Met Éireann, 2020). The same data that was used for the pre-COVID scenario in the COVID analysis, described in Section 5.2.3, was used to analyse the mitigation measure impacts and represented 2019 conditions. The methodology used to analyse the data was the same as that used for the meteorological data in the WS-LUR model development, described in Section 3.3.1. Table 6.18 and Figure 6.7 present the statistics and wind roses for the wind speeds by wind directional sectors for the pre- and post-mitigation scenarios at all modelled locations whilst Table 6.19 and Figure 6.8 present the statistics and wind roses for the wind direction proportions.

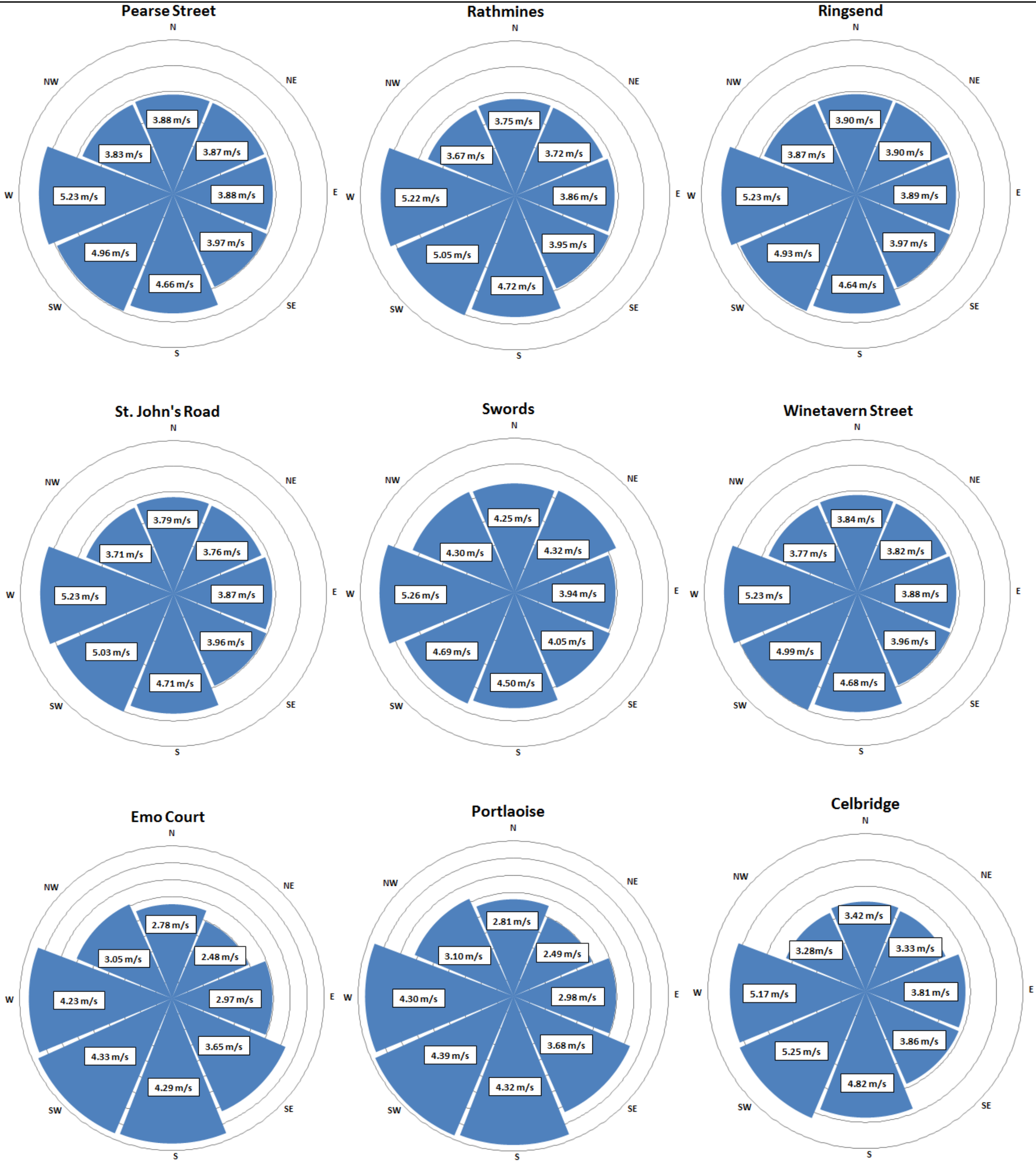
Table 6.18: Wind Speed by Directional Sector for Pre- and Post-Mitigation Measure Scenarios

	WIND SPEED (m/s)							
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	3.60	3.52	3.84	3.93	4.82	5.20	5.23	3.46
Blanchardstown	3.75	3.72	3.86	3.93	4.70	5.03	5.21	3.68
Celbridge	3.42	3.33	3.81	3.86	4.82	5.25	5.17	3.28
Coleraine Street	3.87	3.86	3.88	3.97	4.67	4.97	5.23	3.82
Davitt Road	3.71	3.66	3.86	3.94	4.75	5.10	5.23	3.61
Dún Laoghaire	3.78	3.77	3.87	3.93	4.67	4.99	5.20	3.73
Emo Court	2.78	2.48	2.97	3.65	4.29	4.33	4.23	3.05
Kilkitt	2.69	2.71	2.92	3.27	3.91	3.98	3.16	2.77
Knocklyon	3.57	3.48	3.83	3.92	4.84	5.22	5.23	3.41
Navan	3.37	3.42	3.83	3.65	4.39	4.83	4.88	3.48
Newbridge	3.02	2.68	3.38	3.51	4.68	5.16	4.91	2.99
Pearse Street	3.88	3.87	3.88	3.97	4.66	4.96	5.23	3.83
Portlaoise	2.81	2.49	2.98	3.68	4.32	4.39	4.30	3.10
Rathmines	3.75	3.72	3.86	3.95	4.72	5.05	5.22	3.67
Ringsend	3.90	3.90	3.89	3.97	4.64	4.93	5.23	3.87
Seville Lodge	3.17	2.73	2.95	3.96	4.65	4.81	4.71	3.51
St. Anne's Park	4.05	4.08	3.91	4.01	4.58	4.83	5.24	4.05
St. John's Road	3.79	3.76	3.87	3.96	4.71	5.03	5.23	3.71
Swords	4.25	4.32	3.94	4.05	4.50	4.69	5.26	4.30
Winetavern Street	3.84	3.82	3.88	3.96	4.68	4.99	5.23	3.77
Kildare Village	3.00	2.62	3.31	3.46	4.64	5.11	4.88	3.00
St. Brigid's Cathedral	3.00	2.63	3.32	3.46	4.64	5.12	4.88	3.00
M7 Junction South	3.00	2.61	3.29	3.45	4.64	5.11	4.88	3.00
Tyrrelstown	3.79	3.79	3.87	3.92	4.63	4.95	5.18	3.76
Blanchardstown Business Campus	3.89	3.90	3.89	3.96	4.62	4.91	5.21	3.87





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3.87 m/s
3.88 m/s
3.97 m/s
4.66 m/s
4.96 m/s
5.23 m/s
3.83 m/s
Rathmines
3.75 m/s
3.72 m/s
3.86 m/s
3.95 m/s
4.72 m/s
5.05 m/s
5.22 m/s
3.67 m/s
Ringsend
3.90 m/s
3.90 m/s
3.89 m/s
3.97 m/s
4.64 m/s
4.93 m/s
5.23 m/s
3.87 m/s
St. John's Road
3.79 m/s
3.76 m/s
3.87 m/s
3.96 m/s
4.71 m/s
5.03 m/s
5.23 m/s
3.71 m/s
Swords
4.25 m/s
4.32 m/s
3.94 m/s
4.05 m/s
4.50 m/s
4.69 m/s
5.26 m/s
4.30 m/s
Winetavern Street
3.84 m/s
3.82 m/s
3.88 m/s
3.96 m/s
4.68 m/s
4.99 m/s
5.23 m/s
3.77 m/s
Emo Court
2.78 m/s
2.48 m/s
2.97 m/s
3.65 m/s
4.29 m/s
4.33 m/s
4.23 m/s
3.05 m/s
Portlaoise
2.81 m/s
2.49 m/s
2.98 m/s
3.68 m/s
4.32 m/s
4.39 m/s
4.30 m/s
3.10 m/s
Celbridge
3.42 m/s
3.33 m/s
3.81 m/s
3.86 m/s
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5.17 m/s
3.28m/s
N
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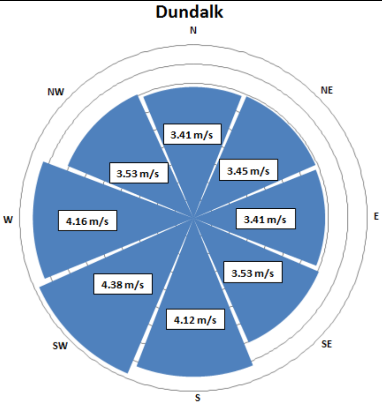
Dundalk
N
NE
E
SE
S
SW
W
NW
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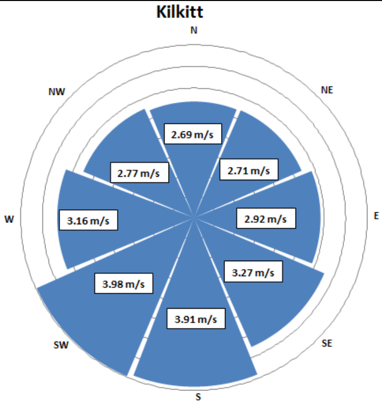
3.41 m/s
3.53 m/s
4.12 m/s
4.38 m/s
4.16 m/s
3.53 m/s


Kilkitt
N
NE
E
SE
S
SW
W
NW
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2.71 m/s
2.92 m/s
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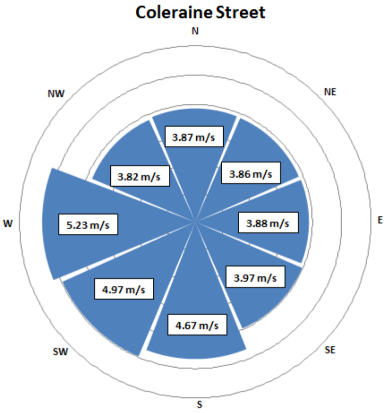
3.91 m/s
3.98 m/s
3.16 m/s
2.77 m/s


Coleraine Street
N
NE
E
SE
S
SW
W
NW
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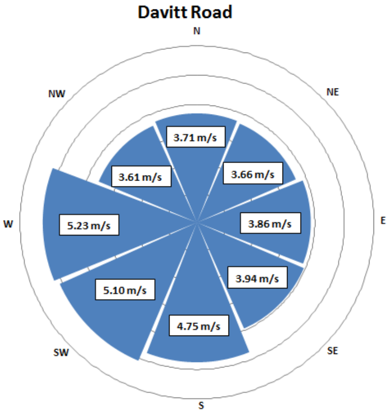
4.97 m/s
5.23 m/s
3.82 m/s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NE
E
SE
S
SW
W
NW
3.71 m/s
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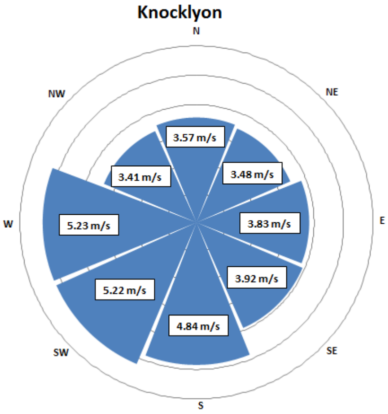
5.23 m/s
3.61 m/s


Knocklyon
N
NE
E
SE
S
SW
W
NW
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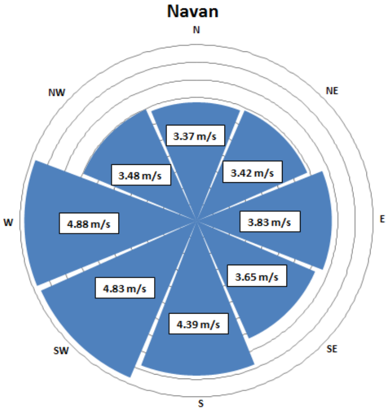
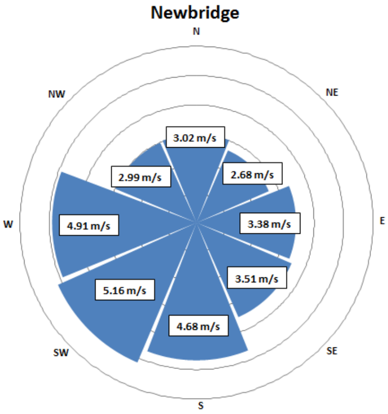
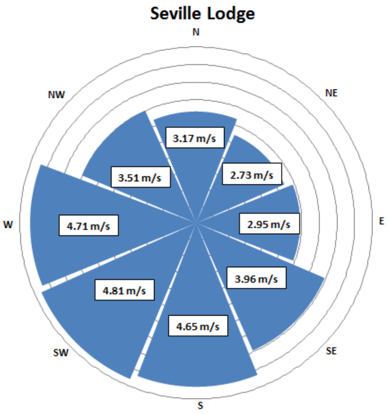
5.23 m/s
3.41 m/s


Navan
N
NE
E
SE
S
SW
W
NW
3.37 m/s
3.42 m/s
3.83 m/s
3.65 m/s
4.39 m/s
4.83 m/s
4.88 m/s
3.48 m/s


Newbridge
N
NE
E
SE
S
SW
W
NW
3.02 m/s
2.68 m/s
3.38 m/s
3.51 m/s
4.68 m/s
5.16 m/s
4.91 m/s
2.99 m/s


Seville Lodge
N
NE
E
SE
S
SW
W
NW
3.17 m/s
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2.95 m/s
3.96 m/s
4.65 m/s
4.81 m/s
4.71 m/s
3.51 m/s

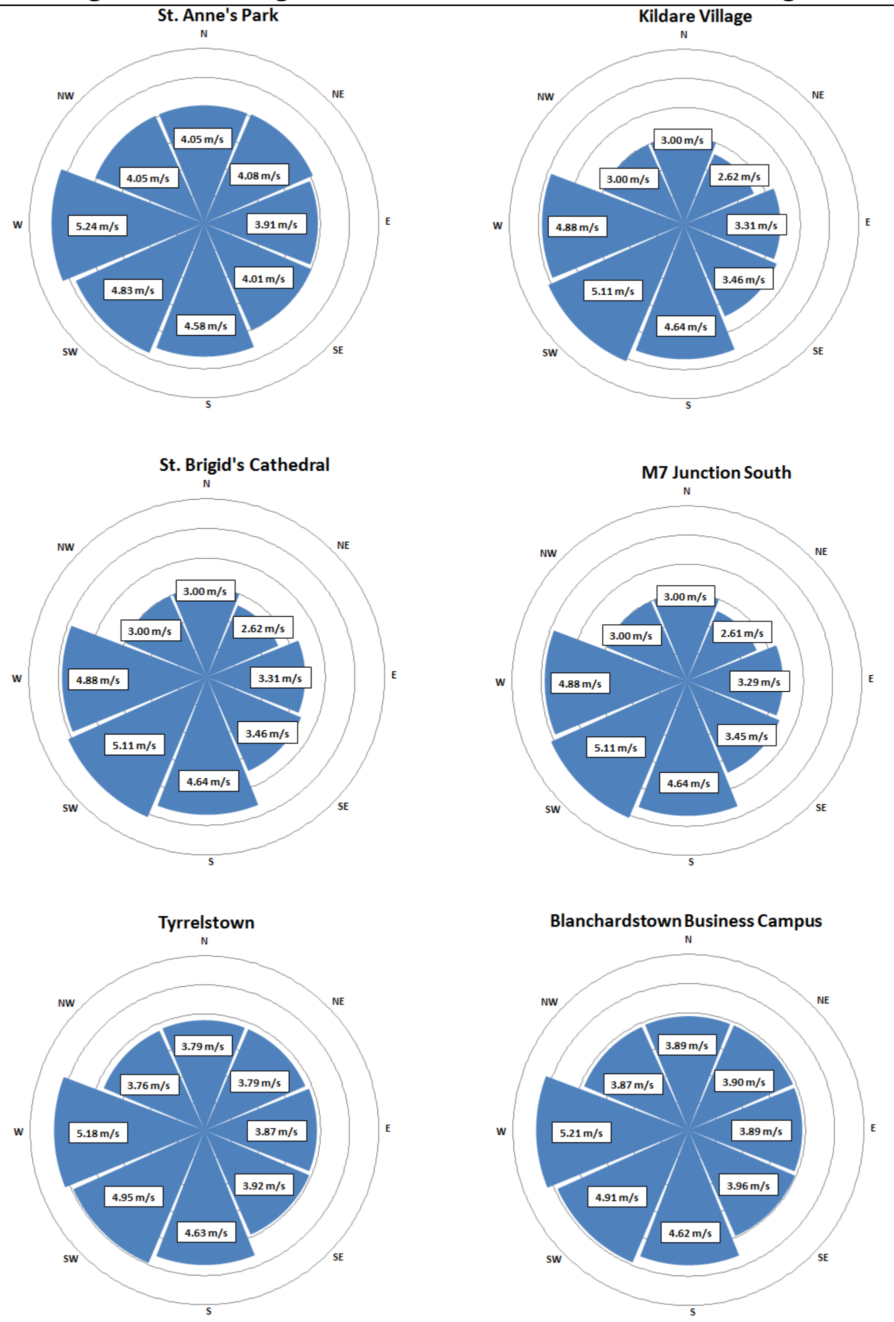
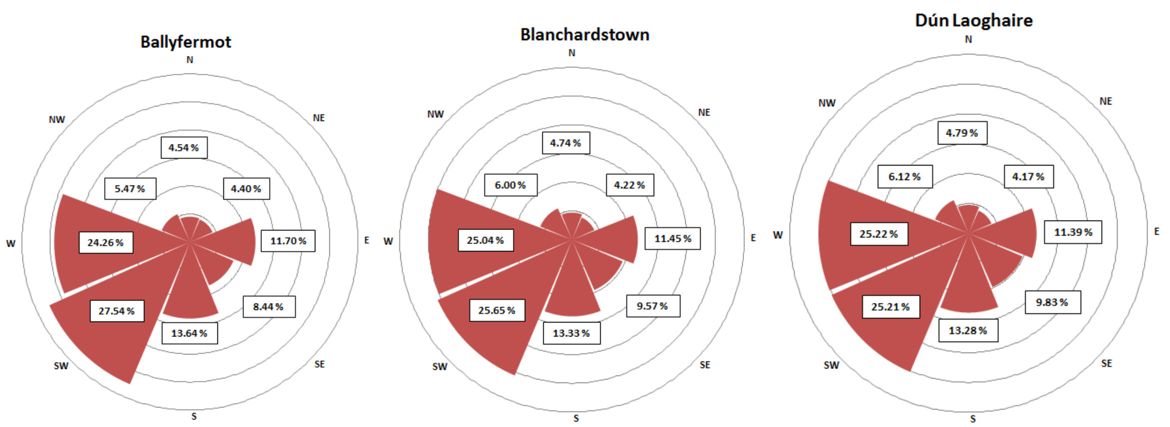
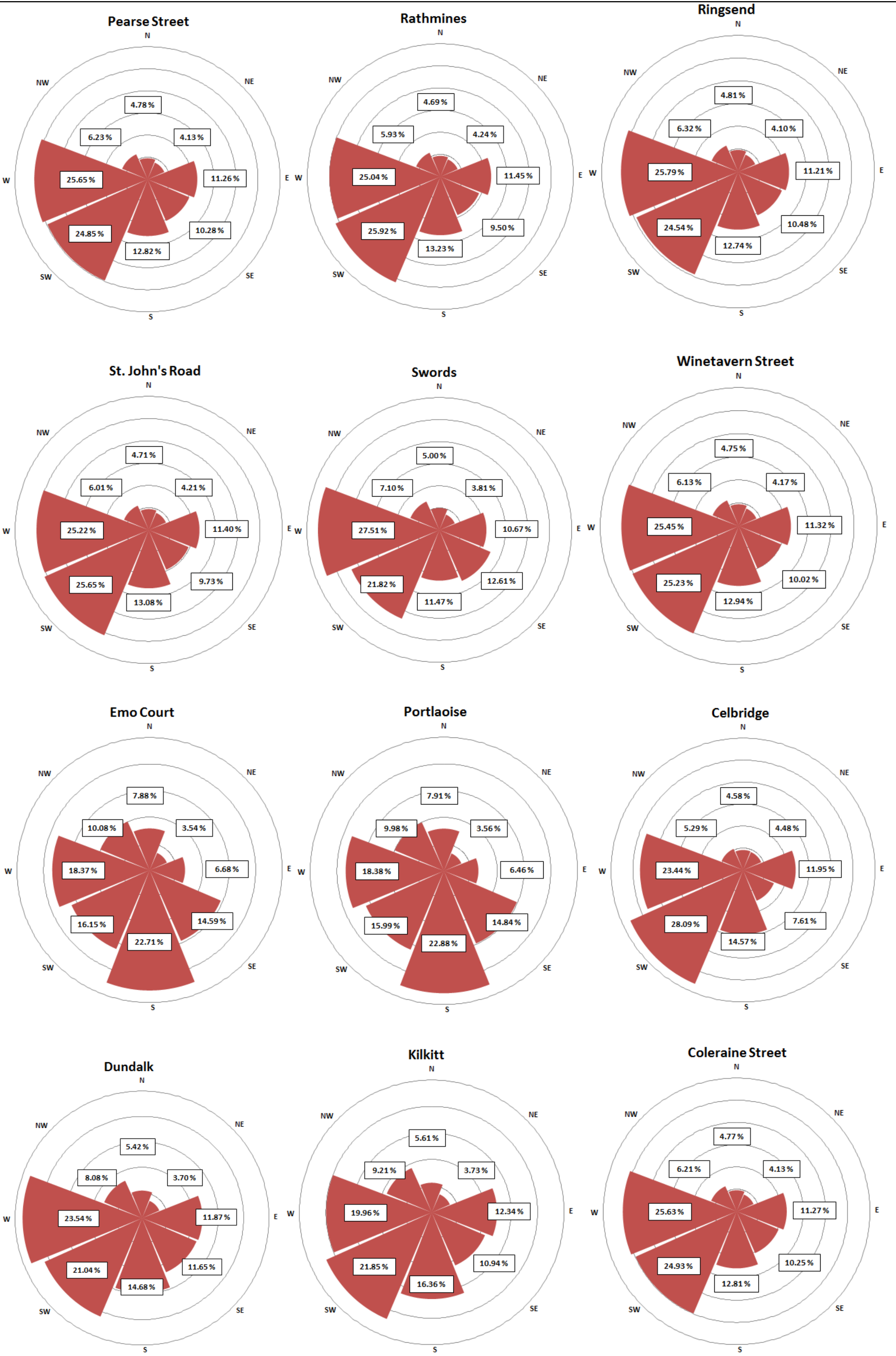


Figure 6.7: Wind Speed Roses Pre- and Post-Mitigation Scenarios

Table 6.19: Wind Direction Proportions by Directional Sector for Pre- and Post-Mitigation Measure Scenarios

	WIND PROPORTION (%)							
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	4.54	4.40	11.70	8.44	13.64	27.54	24.26	5.47
Blanchardstown	4.74	4.22	11.45	9.57	13.33	25.65	25.04	6.00
Celbridge	4.58	4.48	11.95	7.61	14.57	28.09	23.44	5.29
Coleraine Street	4.77	4.13	11.27	10.25	12.81	24.93	25.63	6.21
Davitt Road	4.65	4.28	11.52	9.20	13.33	26.40	24.82	5.79
Dún Laoghaire	4.79	4.17	11.39	9.83	13.28	25.21	25.22	6.12
Emo Court	7.88	3.54	6.68	14.59	22.71	16.15	18.37	10.08
Kilkitt	5.61	3.73	12.34	10.94	16.36	21.85	19.96	9.21
Knocklyon	4.52	4.43	11.76	8.23	13.78	27.79	24.09	5.40
Navan	5.35	4.11	11.85	8.90	16..31	23.42	23.61	6.46
Newbridge	6.43	3.81	9.97	9.83	19.67	22.16	20.94	7.18
Pearse Street	4.78	4.13	11.26	10.28	12.82	24.85	25.65	6.23
Portlaoise	7.91	3.56	6.46	14.84	22.88	15.99	18.38	9.98
Rathmines	4.69	4.24	11.45	9.50	13.23	25.92	25.04	5.93
Ringsend	4.81	4.10	11.21	10.48	12.74	24.54	25.79	6.32
Seville Lodge	8.75	3.90	5.34	13.97	21.82	17.02	18.62	10.58
St. Anne’s Park	4.90	3.97	10.98	11.40	12.21	23.35	26.53	6.66
St. John’s Road	4.71	4.21	11.40	9.73	13.08	25.65	25.22	6.01
Swords	5.00	3.81	10.67	12.61	11.47	21.82	27.51	7.10
Winetavern Street	4.75	4.17	11.32	10.02	12.94	25.23	25.45	6.13
Kildare Village	6.82	3.64	9.48	10.61	20.42	20.63	20.74	7.67
St. Brigid’s Cathedral	6.78	3.66	9.54	10.52	20.34	20.79	20.76	7.61
M7 Junction South	6.87	3.62	9.41	10.71	20.51	20.45	20.71	7.73
Tyrrelstown	4.85	4.13	11.36	10.01	13.35	24.74	25.30	6.24
Blanchardstown Business Campus	4.85	4.08	11.22	10.51	12.88	24.33	25.76	6.37




Pearse Street
4.78 %
4.13 %
11.26 %
10.28 %
12.82 %
24.85 %
25.65 %
6.23 %
Rathmines
4.69 %
4.24 %
11.45 %
9.50 %
13.23 %
25.92 %
25.04 %
5.93 %
Ringsend
4.81 %
4.10 %
11.21 %
10.48 %
12.74 %
24.54 %
25.79 %
6.32 %
St. John's Road
4.71 %
4.21 %
11.40 %
9.73 %
13.08 %
25.65 %
25.22 %
6.01 %
Swords
5.00 %
3.81 %
10.67 %
12.61 %
11.47 %
21.82 %
27.51 %
7.10 %
Winetavern Street
4.75 %
4.17 %
11.32 %
10.02 %
12.94 %
25.23 %
25.45 %
6.13 %
Emo Court
7.88 %
3.54 %
6.68 %
14.59 %
22.71 %
16.15 %
18.37 %
10.08 %
Portlaoise
7.91 %
3.56 %
6.46 %
14.84 %
22.88 %
15.99 %
18.38 %
9.98 %
Celbridge
4.58 %
4.48 %
11.95 %
7.61 %
14.57 %
28.09 %
23.44 %
5.29 %
Dundalk
5.42 %
3.70 %
11.87 %
11.65 %
14.68 %
21.04 %
23.54 %
8.08 %
Kilkitt
5.61 %
3.73 %
12.34 %
10.94 %
16.36 %
21.85 %
19.96 %
9.21 %
Coleraine Street
4.77 %
4.13 %
11.27 %
10.25 %
12.81 %
24.93 %
25.63 %
6.21 %

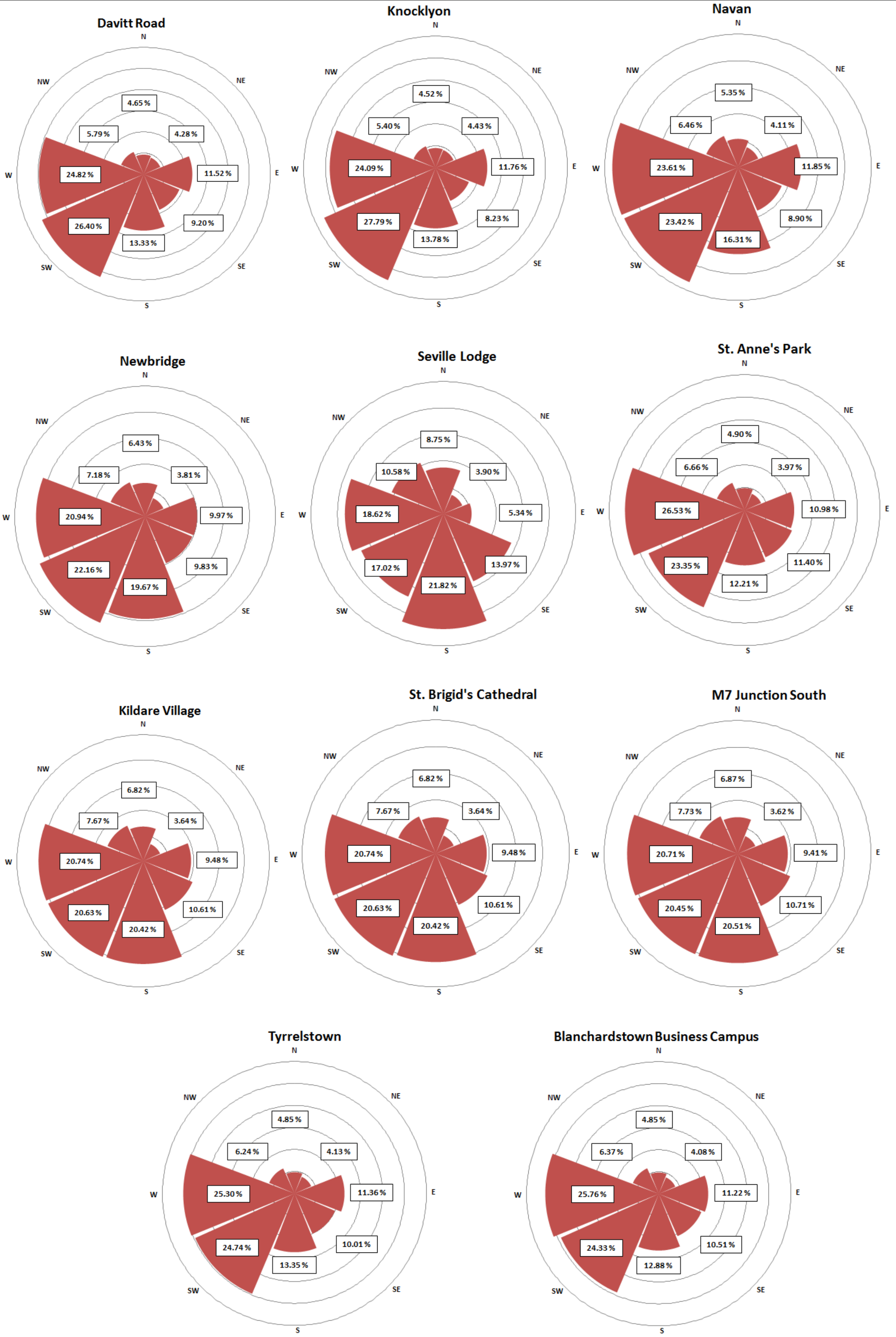


Figure 6.8: Wind Direction Proportion Roses Pre- and Post-Mitigation Scenarios

The road density data used for this analysis was obtained from the National Transport Authority's model for the east region of Ireland (National Transport Authority, 2020). This contained information in relation to all links located in the province of Leinster and was the same data used for the WS-LUR model development, described in Section 3.3.4, which represented the 2016 to 2018 period. The pre- and post-mitigation measure scenarios were based on the same model version; therefore there were no inconsistencies between the road densities for both scenarios.

The land use data was sourced from the European Environment Agency / Copernicus database (European Environment Agency & Copernicus, 2020) and was the same data used to determine the pre-COVID scenario in the COVID analysis, which represented 2018 conditions and is described in Section 5.2.5. The methodology used to analyse the data was the same as that used for the land use data in the WS-LUR model development, described in Section 3.3.2. The land use was unchanged for the post-mitigation scenario due to the assumption within the traffic modelling which spread the relocated businesses evenly across the entire Central Statistics Office Small Areas. Therefore, the land use changes would be minimal across all directional sectors.

6.1.1.5. Methodology and Data Summary

The statistics generated as part of the data analyses described between Sections 6.1.1.2 and 6.1.1.4 for the Blanchardstown Business Hub Relocation scenario were collated and input into the WS-LUR model. The manual entry approach was selected within the model and the statistics for each of the predictor variables were input into the respective sections (Section A for meteorological data; Section B for land use data; Section C for commercial properties data and Section D for traffic data (IDWVKT and road density)). The modelled concentrations for the post-mitigation measure scenario were generated for all modelled locations and compared with modelled concentrations for the pre-mitigation measure scenario (2019 conditions), which were calculated previously in the COVID analysis described in Sections 5.2 and 5.3. Results of the concentration changes / comparison are provided in the following section.

6.1.2. Results

The results of the data analysis described within Section 6.1.1 were collated and input into the WS-LUR model using the manual entry approach (described in Chapter 4) to determine the modelled ambient NO_2 concentrations at each of the modelled locations for both the pre- and post-mitigation measure scenarios. Table 6.20 and Figure 6.9 present the concentrations for pre- (2019) and the post-mitigation measure (Blanchardstown Business Hub Relocation) scenarios and the resultant difference in ambient NO_2 concentration at all modelled locations identified for this analysis. As a result of the relocation of job attractions from the Blanchardstown region to the Kildare Town region, changes in traffic flows were not limited to the areas in close proximity to the original and new business locations, with effects being experienced throughout the Leinster province, as shown in Figure 6.1. The changes in the origin / destination of the trips within the National Transport Model altered the flows on the majority of routes, with reductions of up to 10% in AADT, with full details provided in Section 6.1.1.2. The overall aim of the mitigation measures was to reduce the overall distance travelled by commuters and reduce congestion in an area experiencing high NO_2 concentrations. As can be seen in Table 6.20 these changes resulted in reduced ambient NO_2 concentrations around a number of commuter towns such as Newbridge, Navan and Celbridge, which display reductions of 0.3, 0.2 and 0.5 $\mu g / m^3$ respectively. Significant reductions are displayed in the Dublin City Centre locations; Coleraine Street, Pearse Street, Ringsend, St. John's Road and Winetavern Street with reductions of 0.5, 0.7, 0.5, 1.9 and 0.9 $\mu g / m^3$ respectively. These reductions are mainly due to the traffic changes as described in Section 6.1.1.2, and are critical in these locations which are continuously approaching the Directive 2008/50/EC annual mean limit concentration of 40 μg / m^3 (European Union, 2008). Varying results were achieved at the other Dublin modelled locations, located outside of the city centre. The Dun Laoghaire and Davitt Road monitoring station locations display increases of 0.2 and 2.3 μg / m^3 respectively, which are mainly attributable to the changes in flows described in Section 6.1.1.2 and Table 6.2 in combination with major increases in IDWVKT in the pre-dominant west and southwest wind direction sectors. The remaining Dublin modelled locations all display positive results with reductions in the range of 0.3 and 1.7 μg / m^3. Concentration reductions in close proximity to the original business locations (the Blanchardstown EPA monitoring station and the Tyrrelstown and Blanchardstown Business Campus additional locations) ranged from 0.4 to 1.3 μg / m^3. The 1.3 μg / m^3 reduction occurring at the Blanchardstown EPA station, which similar to the city centre locations, experiences ambient NO_2 concentrations close to the Directive 2008/50/EC limit values.

The changes in concentrations at the additional locations identified for this analysis range from +0.1 to -0.4 μg / m^3, highlighting that the relocation of businesses had limited negative impacts in terms of NO_2 concentrations. As expected, reductions were experienced in the number of vehicles which continued travelling along the M7 motorway past Kildare Town and towards Blanchardstown. This was one of the main factors which lead to minimal changes in NO_2 concentrations in the Kildare Town locations as it offset the increase in trip attractions and traffic flows in the area, as described in Section 6.1.1.2. The reductions in IDWVKT in the east and southwest sectors of the Kildare Village location, as shown in Section 6.1.1.2, is evidence of this change. The amount of traffic getting on to the motorway via the link west of Kildare Village also reduced considerably with the relocation of trip attractions to Kildare. This reduction in the motorway flows is also confirmed by the reductions in IDWVKT in the north sector of the M7 Junction South location. In the west sector of this location, the old Dublin Road (main route to Dublin prior to the construction of the motorway) also experienced significant reductions in flows and was another route for commuters to get onto the M7 motorway to travel towards Dublin.

Table 6.20: Blanchardstown Business Hub Relocation Impacts on 2019 Concentrations

Monitoring Station	Modelled Scenario	Modelled Concentration (µg / m^3)	Difference (µg / m^3)
Ballyfermot, Dublin	2019	33.5	-1.7
	2019 Blanch. Business Hub Relocation	31.8	
Blanchardstown, Dublin	2019	39.8	-1.3
	2019 Blanch. Business Hub Relocation	38.5	
Celbridge, Kildare	2019	13.6	-0.5
	2019 Blanch. Business Hub Relocation	13.0	
Coleraine Street, Dublin	2019	39.9	-1.2
	2019 Blanch. Business Hub Relocation	38.7	
Davitt Road, Dublin	2019	34.8	2.3
	2019 Blanch. Business Hub Relocation	37.0	
Dun Laoghaire, Dublin	2019	22.7	0.2
	2019 Blanch. Business Hub Relocation	22.9	
Emo Court, Laois	2019	9.0	-0.1
	2019 Blanch. Business Hub Relocation	8.9	
Kilkitt, Monaghan	2019	4.8	-0.0
	2019 Blanch. Business Hub Relocation	4.8	
Knocklyon, Dublin	2019	21.3	-1.0
	2019 Blanch. Business Hub Relocation	20.3	
Navan, Meath	2019	17.2	-0.2
	2019 Blanch. Business Hub Relocation	16.9	
Newbridge, Kildare	2019	12.1	-0.3
	2019 Blanch. Business Hub Relocation	11.8	
Pearse Street, Dublin	2019	38.0	-0.7
	2019 Blanch. Business Hub Relocation	37.3	
Portlaoise, Laois	2019	15.8	-0.2
	2019 Blanch. Business Hub Relocation	15.5	
Rathmines, Dublin	2019	30.5	-0.7
	2019 Blanch. Business Hub Relocation	29.8	
Ringsend, Dublin	2019	21.4	-0.5
	2019 Blanch. Business Hub Relocation	20.8	
Seville Lodge, Kilkenny	2019	4.6	-0.0
	2019 Blanch. Business Hub Relocation	4.6	
St. Anne’s Park, Dublin	2019	14.8	-0.3
	2019 Blanch. Business Hub Relocation	14.5	
St. John’s Road, Dublin	2019	34.1	-1.9
	2019 Blanch. Business Hub Relocation	32.2	

Monitoring Station	Modelled Scenario	Modelled Concentration (µg / m^3)	Difference (µg / m^3)
Swords, Dublin	2019	21.8	-0.6
	2019 Blanch. Business Hub Relocation	21.2	
Winetavern Street, Dublin	2019	44.0	-0.9
	2019 Blanch. Business Hub Relocation	43.0	
Kildare Village**	2019	15.2	-0.4
	2019 Blanch. Business Hub Relocation	14.8	
Saint Brigid's Cathedral / Market Square **	2019	10.0	0.1
	2019 Blanch. Business Hub Relocation	10.1	
M7 Junction South**	2019	3.0	-0.0
	2019 Blanch. Business Hub Relocation	3.0	
Tyrrelstown**	2019	9.8	-0.4
	2019 Blanch. Business Hub Relocation	9.4	
Blanchardstown Business Campus**	2019	9.5	-0.6
	2019 Blanch. Business Hub Relocation	8.9	

*** Additional (non-EPA monitoring locations) modelled locations identified as key sites to determine the potential impact of mitigation measure on NO_2 concentrations*

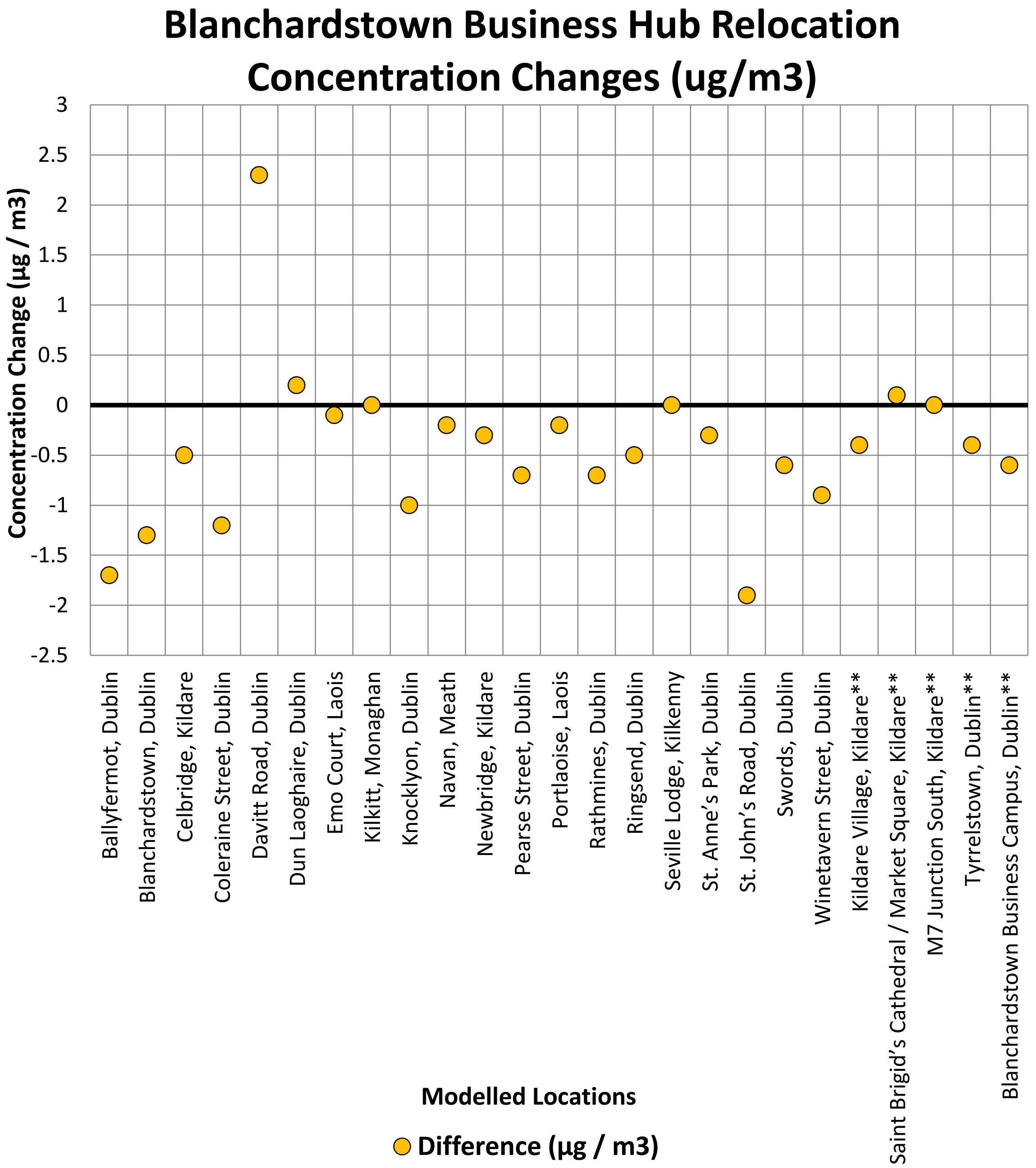


Figure 6.9: Blanchardstown Business Hub Relocation Concentration Change at Modelled Locations

6.1.3. Conclusion

This analysis evaluated the effects of relocating businesses, which were not dependent on the locale, to an area experiencing lower levels of traffic and pollution than the original location of the businesses. This mitigation measure focused on determining the changes in NO_2 concentrations due to the relocation of a number of trip attractions, but it also highlighted the importance for air quality of good site selection in the development of future businesses.

A number of positive impacts expected at both the original and new business locations were confirmed in this analysis. These include:

- The number of trips within the Blanchardstown area reduced and this resulted in reductions in total traffic and IDWVKT. NO_2 concentrations reduced by between 0.4 and 1.3 μg / m^3 in the Blanchardstown area.
- The flows on major routes towards the Greater Dublin Area from all directions reduced and were expected to reduce congestion issues in the Greater Dublin Area, which the modelled concentrations confirmed with reductions of 0.5 to 1.9 μg / m^3 in NO_2 concentrations in Dublin City Centre locations and reductions of 0.3 to 1.7 μg / m^3 across the majority of the Greater Dublin Area.
- The reductions in flows along major routes also improved air quality across a number of towns in the Leinster region with reductions of 0.5, 0.2, 0.3 and 0.2 μg / m^3 at Newbridge, Celbridge, Navan and Portlaoise respectively.
- Despite moving a number of businesses to Kildare Town and the increased flows towards the town, there were no significant increases in NO_2 concentrations at any of the additional locations identified for the analysis with concentrations changing by -0.4, +0.1 and 0 μg / m^3 at Kildare Village, St. Brigid’s Cathedral and M7 Junction South respectively.

6.2. Public Service Vehicles Diesel Removal

Section 2.4.3.3 identified that public service vehicles make up a larger proportion of the vehicles that operate in urban areas and that the majority of these vehicles are fuelled by diesel. This mitigation measure aims to influence the change from diesel to greener fuelled options within the public service vehicles fleet in Ireland, which in the last 10 years has seen a substanital increase and dependency on diesel. As there is a larger proportion of these vehicles located in the major cities, it could be expected that any increase in newer Euro Class vehicles or greener fuel options would have a significant improvement on air quality in many of the areas which are currently experiencing levels close to the Directive 2008/50/EC limit on NO_2. This mitigation measures also targets vehicles which are already regulated / owned by government authorities which would assist the process of transitioning from diesel to greener fuel options and would provide a definitive timeline as to when the mitigation measure can be fully implemented. The existing vehicle fleet was determined using the Irish Bulletin of Vehicle and Driver Statistics (Department of Transport, Tourism and Sport, 2020), as described in Section 6.1.1.3. This mitigation measure removed all diesel powered vehicles from both the SPSV and LPSV fleets and replaced them with electric powered vehicles. New emission weightings were calculated using the altered fleets for both the SPSVs and LPSVs using Section D3 of the model, described in Section 4.1.5.

All EPA monitoring station locations within the Greater Dublin Area were modelled in this analysis. This mitigation measure targets small and large public service vehicles which predominantly operate in urban and suburban areas, therefore, the decision was made to focus on the areas where the greatest impacts would be achieved and as these areas are also the most heavily polluted areas in the country.

6.2.1. Methodology and Data

6.2.1.1. Meteorological, Road Density, Inverse Distance Weighted Vehicle Kilometres Travelled, Commercial Properties and Land Use Data

This section introduces the sources of data for the variables which were unaffected by the mitigation measure (meteorological, road density, IDWVKT, commercial properties and land use) and whose values were therefore the same in both the pre- and post-mitigation scenarios. The methodology used to analyse the data was the same as that used to develop the background data for the WS-LUR model described in Chapter 3.

The meteorological data used in this analysis was obtained from the Met Éireann historical database and included data for all monitoring stations including offshore stations (Met Éireann, 2020). The same data that was used for the pre-COVID scenario in the COVID analysis was used to analyse the mitigation measure impacts and represented 2019 conditions, as described in Section 5.2.3. The methodology used to analyse the data was the same as that used for the meteorological data in the WS-LUR model development, described in Section 3.3.1. Table 6.21 and Figure 6.10 present the statistics and wind roses for the wind speeds by wind directional sectors for the pre- and post-mitigation scenarios at all modelled locations whilst Table 6.22 and Figure 6.11 present the statistics and wind roses for the wind direction proportions.

Table 6.21: Wind Speed by Directional Sector for Pre- and Post-Mitigation Measure Scenarios

WIND SPEED (m/s)								
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	3.60	3.52	3.84	3.93	4.82	5.20	5.23	3.46
Blanchardstown	3.75	3.72	3.86	3.93	4.70	5.03	5.21	3.68
Coleraine Street	3.87	3.86	3.88	3.97	4.67	4.97	5.23	3.82
Davitt Road	3.71	3.66	3.86	3.94	4.75	5.10	5.23	3.61
Dún Laoghaire	3.78	3.77	3.87	3.93	4.67	4.99	5.20	3.73
Pearse Street	3.88	3.87	3.88	3.97	4.66	4.96	5.23	3.83
Rathmines	3.75	3.72	3.86	3.95	4.72	5.05	5.22	3.67
Ringsend	3.90	3.90	3.89	3.97	4.64	4.93	5.23	3.87
St. John’s Road	3.79	3.76	3.87	3.96	4.71	5.03	5.23	3.71
Swords	4.25	4.32	3.94	4.05	4.50	4.69	5.26	4.30
Winetavern Street	3.84	3.82	3.88	3.96	4.68	4.99	5.23	3.77

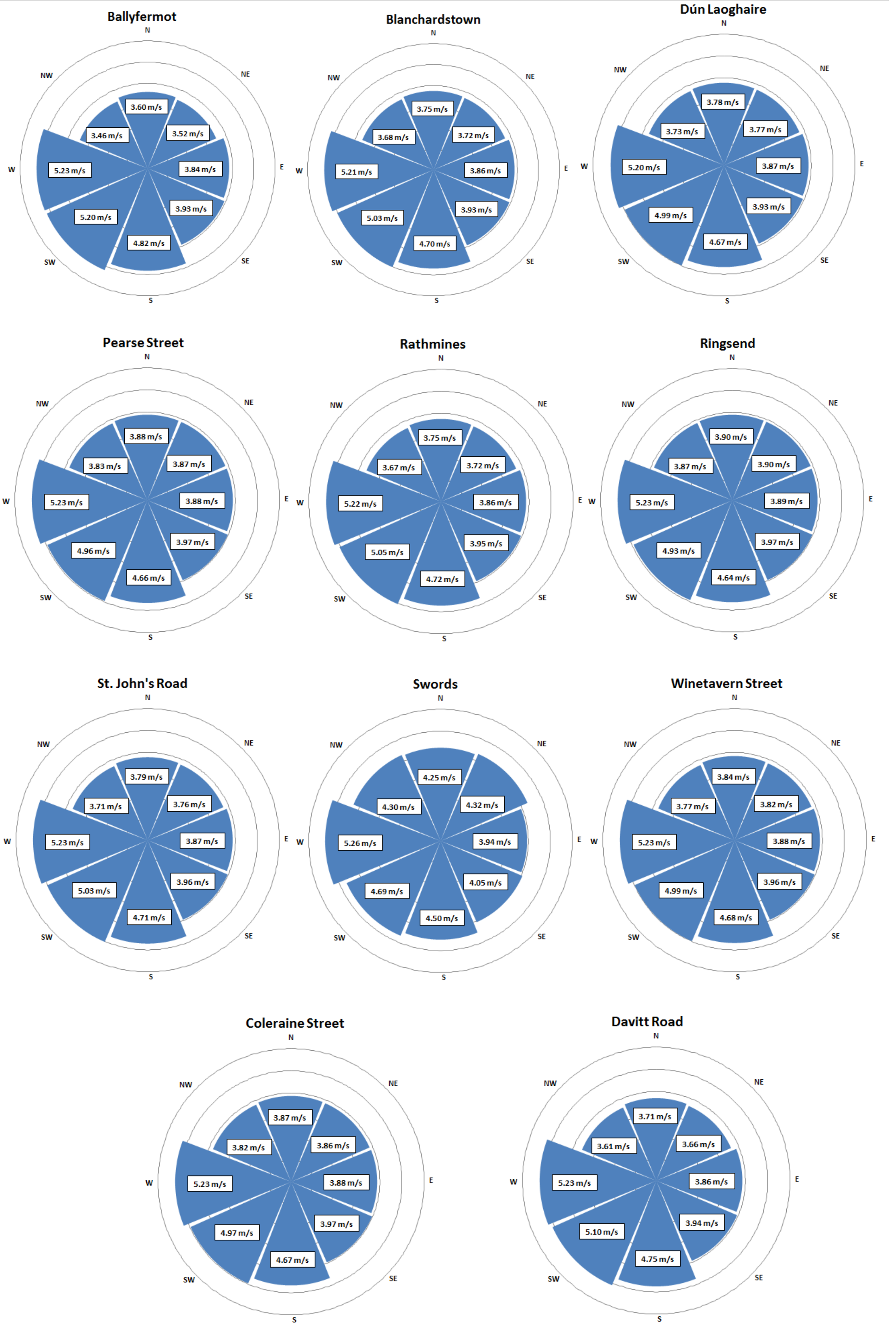
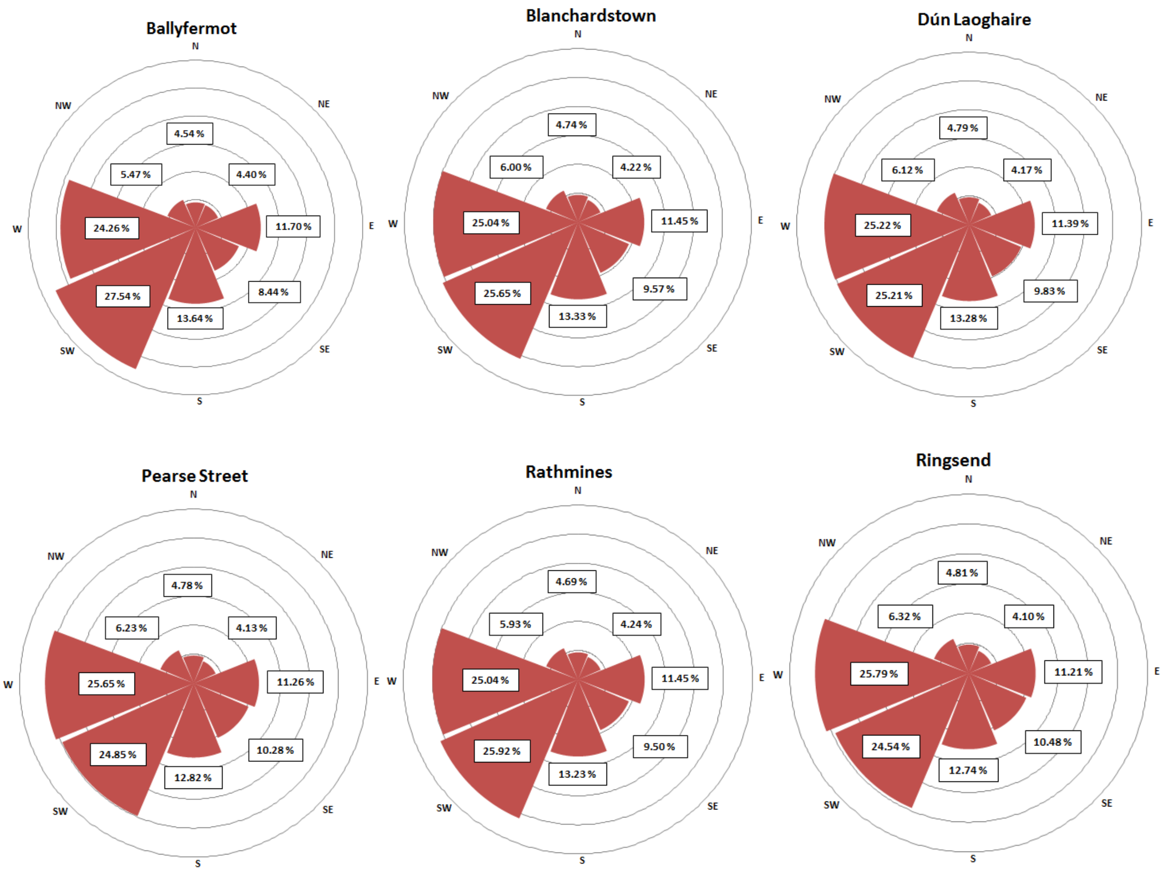


Figure 6.10: Wind Speed Roses for Pre- and Post-Mitigation Scenarios

Table 6.22: Wind Direction Proportions by Directional Sector for Pre- and Post-Mitigation Measure Scenarios

	WIND PROPORTION (%)							
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	4.54	4.40	11.70	8.44	13.64	27.54	24.26	5.47
Blanchardstown	4.74	4.22	11.45	9.57	13.33	25.65	25.04	6.00
Coleraine Street	4.77	4.13	11.27	10.25	12.81	24.93	25.63	6.21
Davitt Road	4.65	4.28	11.52	9.20	13.33	26.40	24.82	5.79
Dún Laoghaire	4.79	4.17	11.39	9.83	13.28	25.21	25.22	6.12
Pearse Street	4.78	4.13	11.26	10.28	12.82	24.85	25.65	6.23
Rathmines	4.69	4.24	11.45	9.50	13.23	25.92	25.04	5.93
Ringsend	4.81	4.10	11.21	10.48	12.74	24.54	25.79	6.32
St. John's Road	4.71	4.21	11.40	9.73	13.08	25.65	25.22	6.01
Swords	5.00	3.81	10.67	12.61	11.47	21.82	27.51	7.10
Winetavern Street	4.75	4.17	11.32	10.02	12.94	25.23	25.45	6.13



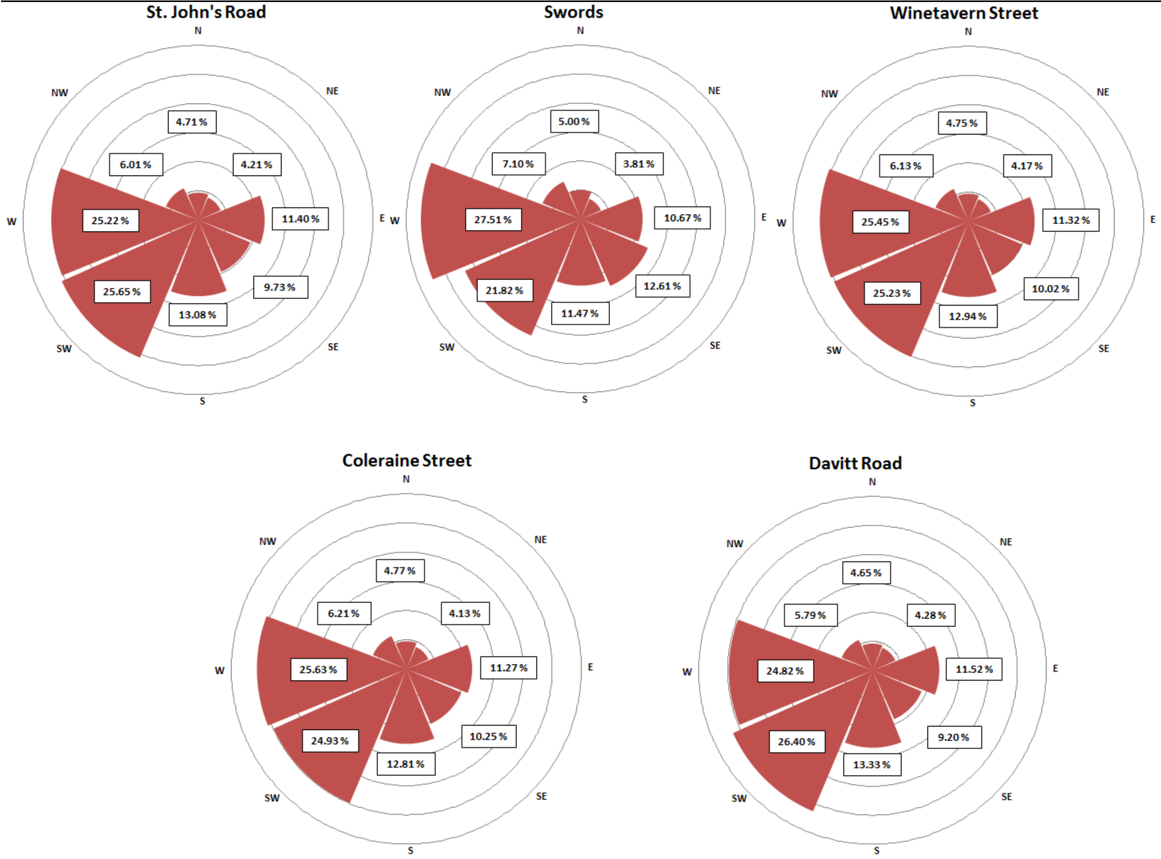


Figure 6.11: Wind Direction Proportion Roses for Pre- and Post-Mitigation Scenarios

The road density and IDWVKT data used for this analysis was obtained from the National Transport Authority's model for the east region of Ireland (National Transport Authority, 2020). This contained information in relation to all links located in the province of Leinster and was the same output used for the analysis of the performance of the ambient NO_2 concentration model during the 2016 to 2018 period, as described in Sections 5.2.1 and 5.2.5. This mitigation measure focused on altering only the vehicle fleet breakdown to determine the changes in ambient NO_2 concentration; therefore the road density and inverse distance weighted vehicle kilometres travelled statistics were the same for the pre- and post-mitigation measure scenarios. The methodology used to analyse the data was the same as that used for the IDWVKT and road density data in the WS-LUR model development, described in Section 3.3.4.

The commercial properties data was sourced from An Post / Geodirectory and represented 2019 conditions (GeoDirectory, 2020). The data for the pre-mitigation measure scenario was the same as that used for the pre-COVID scenario, described in Section 5.2.2. The mitigation measure focused on the vehicle fleet breakdown therefore the commercial properties were unchanged for the pre- and post-mitigation measure scenarios. The methodology used to analyse the data was the same as that used for the commercial properties data in the WS-LUR model development, described in Section 3.3.3.

The land use data was sourced from the European Environment Agency / Copernicus database (European Environment Agency & Copernicus, 2020) and was the same data used to represent the 2018 conditions in the COVID analysis, as described in Section 5.2.5. The methodology used to analyse the data was the same as that used for the land use data in the WS-LUR model development, described in Section 3.3.2.

6.2.1.2. Vehicle Fleet Data

In this section the altered SPSV and LPSV fleet breakdowns are introduced and the resultant NO_2 emission weighting for the SPSVs and LPSVs in the post-mitigation measure scenario are determined. The pre-mitigation measure scenario represented the national vehicle fleet in 2019 conditions and the methodology used to determine the weightings are described in Section 6.1.1.3. As part of this mitigation measure, the 2019 SPSV and LPSV fleet breakdowns were altered to remove the proportion categorised as diesel fuelled vehicles and replace it with the same percentage of electric powered vehicles. The model then calculated new average NO_2 Emission Weightings for the small and large public service vehicle categories. Table 6.23 identifies the changes within the breakdown of the small public service vehicles fleet and the resultant average NO_2 emission weightings for the pre- and post-mitigation measures scenarios. The weighting reduced considerably due to the removal of the heaviest emitting vehicles (diesel) from the fleet and replacement by electric vehicles which do not emit NO_2.

Table 6.23: Small Public Service Vehicle Fleet Changes in Vehicle Breakdown and Average Emission Weighting

Fuel Type / Engine Size	Euro Class	Pre-Mitigation Percentage	Post-Mitigation Percentage
Petrol Small	Euro 3 - 98/69/EC I	0.006%	0.006%
	Euro 4 - 98/69/EC II	0.014%	0.014%
	Euro 5 - EC 715/2007	0.015%	0.015%
	Euro 6 up to 2016	0.004%	0.004%
	Euro 6 2017 - 2019	0.008%	0.008%
Petrol Medium	Euro 3 - 98/69/EC I	<0.001%	<0.001%
	Euro 4 - 98/69/EC II	0.001%	0.001%
	Euro 5 - EC 715/2007	0.001%	0.001%
	Euro 6 up to 2016	<0.001%	<0.001%
	Euro 6 2017 - 2019	0.001%	0.001%
Petrol Large	Euro 3 - 98/69/EC I	<0.001%	<0.001%
	Euro 4 - 98/69/EC II	<0.001%	<0.001%
	Euro 5 - EC 715/2007	<0.001%	<0.001%
	Euro 6 up to 2016	<0.001%	<0.001%
	Euro 6 2017 - 2019	<0.001%	<0.001%
Diesel Small	Euro 4 - 98/69/EC II	0.204%	0%
	Euro 5 - EC 715/2007	0.216%	0%
	Euro 6 up to 2016	0.059%	0%
	Euro 6 2017 - 2019	0.118%	0%
Diesel Medium	Euro 3 - 98/69/EC I	0.005%	0%
	Euro 4 - 98/69/EC II	0.011%	0%
	Euro 5 - EC 715/2007	0.012%	0%
	Euro 6 up to 2016	0.003%	0%
	Euro 6 2017 - 2019	0.007%	0%
Diesel Large	Euro 3 - 98/69/EC I	<0.001%	0%
	Euro 4 - 98/69/EC II	0.001%	0%
	Euro 5 - EC 715/2007	0.001%	0%
	Euro 6 up to 2016	<0.001%	0%
	Euro 6 2017 - 2019	<0.001%	0%
Hybrid Petrol Small	Euro 4 and Later	0.08%	0.08%
Hybrid Petrol Medium	Euro 4 and Later	0.005%	0.005%
Hybrid Petrol Large	Euro 4 and Later	<0.001%	<0.001%
Ethanol 85	Euro 4	<0.001%	<0.001%
	Euro 5	<0.001%	<0.001%
	Euro 6	<0.001%	<0.001%

Fuel Type / Engine Size	**Euro Class**	**Pre-Mitigation Percentage**	**Post-Mitigation Percentage**
Electric	-	0.002%	0.638%
Total		**0.77%**	**0.77%**
Average NO_2 Emission Weighting		**1.428**	**0.001**

Table 6.24 shows the changes in the large public service vehicle fleet breakdown and resultant average emission weightings. In the pre-mitigation scenario it was assumed that the large public service vehicles fleet was half urban buses and half coaches as the vehicle flows in the traffic data did not account for the different large public service vehicle types. Therefore, the Euro Class breakdown for the urban buses were the same as the coaches in the large public service vehicle fleet. The entire fleet was categorised as diesel in the 2019 scenario whilst in the post-mitigation measure scenario it was decided to remove the diesel powered vehicles in the urban buses category as the majority of this type of large public service vehicle are publically owned (Department of Transport, Tourism and Sport, 2020) and therefore the transition towards greener fuel options can be controlled by the government departments. The average emission weighting reduced by more than 50% from 3.269 to 1.454 by removing only the diesel vehicles within the urban coaches category.

Table 6.24: Large Public Service Vehicle Fleet Changes in Vehicle Breakdown and Average Emission Weighting

Vehicle Type	Euro Class	Pre-Mitigation Percentage	Post-Mitigation Percentage
Urban Buses Standard	Conventional	0.006%	0%
	Euro I - 91/542/EEC I	0.006%	0%
	Euro II - 91/542/EEC II	0.006%	0%
	Euro III - 2000	0.007%	0%
	Euro IV - 2005	0.041%	0%
	Euro V - 2008	0.041%	0%
	Euro VI	0.096%	0%
Coaches Standard	Conventional	0.006%	0.006%
	Euro I - 91/542/EEC I	0.006%	0.006%
	Euro II - 91/542/EEC II	0.006%	0.006%
	Euro III - 2000	0.007%	0.007%
	Euro IV - 2005	0.041%	0.041%
	Euro V - 2008	0.041%	0.041%
	Euro VI	0.096%	0.096%
Electric	-	0%	0.203%
Total		**0.41%**	**0.41%**
Average NO_2 Emission Weighting		**3.269**	**1.454**

6.2.1.3. Methodology and Data Summary

The statistics generated as part of the data analyses described between Sections 6.2.1.1 and 6.2.1.2 for the Small Public Service Vehicles and Large Public Service Vehicles Diesel Removal scenario were collated and input into the WS-LUR model. The manual entry approach was selected within the model and the statistics for each of the predictor variables were input into the respective sections (Section A for meteorological data; Section B for land use data; Section C for commercial properties data and Section D for traffic data (IDWVKT and road density)). The modelled concentrations for the post-mitigation measure scenario were generated for all modelled locations and compared with modelled concentrations for the pre-mitigation measure scenario (2019 conditions), which were calculated previously in the COVID analysis described in Sections 5.2 and 5.3. Results of the concentration changes / comparison are provided in the following section.

6.2.2. Results

Table 6.25 and Figure 6.12 present the modelled concentration changes at monitoring station locations within Dublin as a result of removing the diesel fuelled vehicles from the small and large public service vehicle fleets. Overall, this mitigation measure produced positive results throughout, with all modelled locations experiencing reductions in NO_2. The largest reductions in ambient NO_2 concentrations were experienced at modelled locations within the Canal Corden (Pearse Street, Ringsend, St. John’s Road and Winetavern Street; locations shown in Figure 6.1) which have higher proportions of small public service vehicles and large public service vehicles in comparison to the national average as determined by the 5 Cities Demand Management Study (Department of Transport, Tourism and Sport & Systra, 2020 and Department of Transport, Tourism and Sport & Systra, 2020). These reductions ranged from 1.0 to 1.8 $\mu g / m^3$ which equates to reductions of 3.64% to 5.28% in areas which currently experience high levels of NO_2 pollution. The remaining modelled locations, which were in areas further away from the city centre, typically have less public service vehicles travelling along the surrounding routes. The reductions at these locations were in the range of 0.3 and 0.9 $\mu g / m^3$, which equates to a reduction of 1.32% to 2.3% across these modelled locations. The effects were smaller than in city centre locations as the reduction in emission weightings for the SPSVs and LPSVs had a smaller impact on the IDWVKT variable in rural and suburban locations.

Table 6.25: Small Public Service Vehicle and Large Public Service Vehicle Diesel Removal Impacts on 2019 Concentrations

Monitoring Station	Modelled Scenario	Modelled Concentration (µg / m^3)	Difference (µg / m^3)
Ballyfermot, Dublin	Pre-Mitigation Measure	33.5	-0.7
	Post-Mitigation Measure	32.8	
Blanchardstown, Dublin	Pre-Mitigation Measure	39.8	-0.7
	Post-Mitigation Measure	39.0	
Coleraine Street, Dublin	Pre-Mitigation Measure	39.9	-0.9
	Post-Mitigation Measure	39.0	
Davitt Road, Dublin	Pre-Mitigation Measure	34.8	-0.8
	Post-Mitigation Measure	34.0	
Dun Laoghaire, Dublin	Pre-Mitigation Measure	22.7	-0.3
	Post-Mitigation Measure	22.4	
Pearse Street, Dublin*	Pre-Mitigation Measure	38.0	-1.6
	Post-Mitigation Measure	36.3	
Rathmines, Dublin	Pre-Mitigation Measure	30.5	-0.6
	Post-Mitigation Measure	30.0	
Ringsend, Dublin*	Pre-Mitigation Measure	21.4	-1.0
	Post-Mitigation Measure	20.4	
St. John’s Road, Dublin*	Pre-Mitigation Measure	34.1	-1.8
	Post-Mitigation Measure	32.3	
Swords, Dublin	Pre-Mitigation Measure	21.8	-0.3
	Post-Mitigation Measure	21.4	
Winetavern Street, Dublin*	Pre-Mitigation Measure	44.0	-1.6
	Post-Mitigation Measure	42.4	

** Modelled locations within Canal Corden where the Five Cities Demand Study results were used to define the number of cars which were taxis*

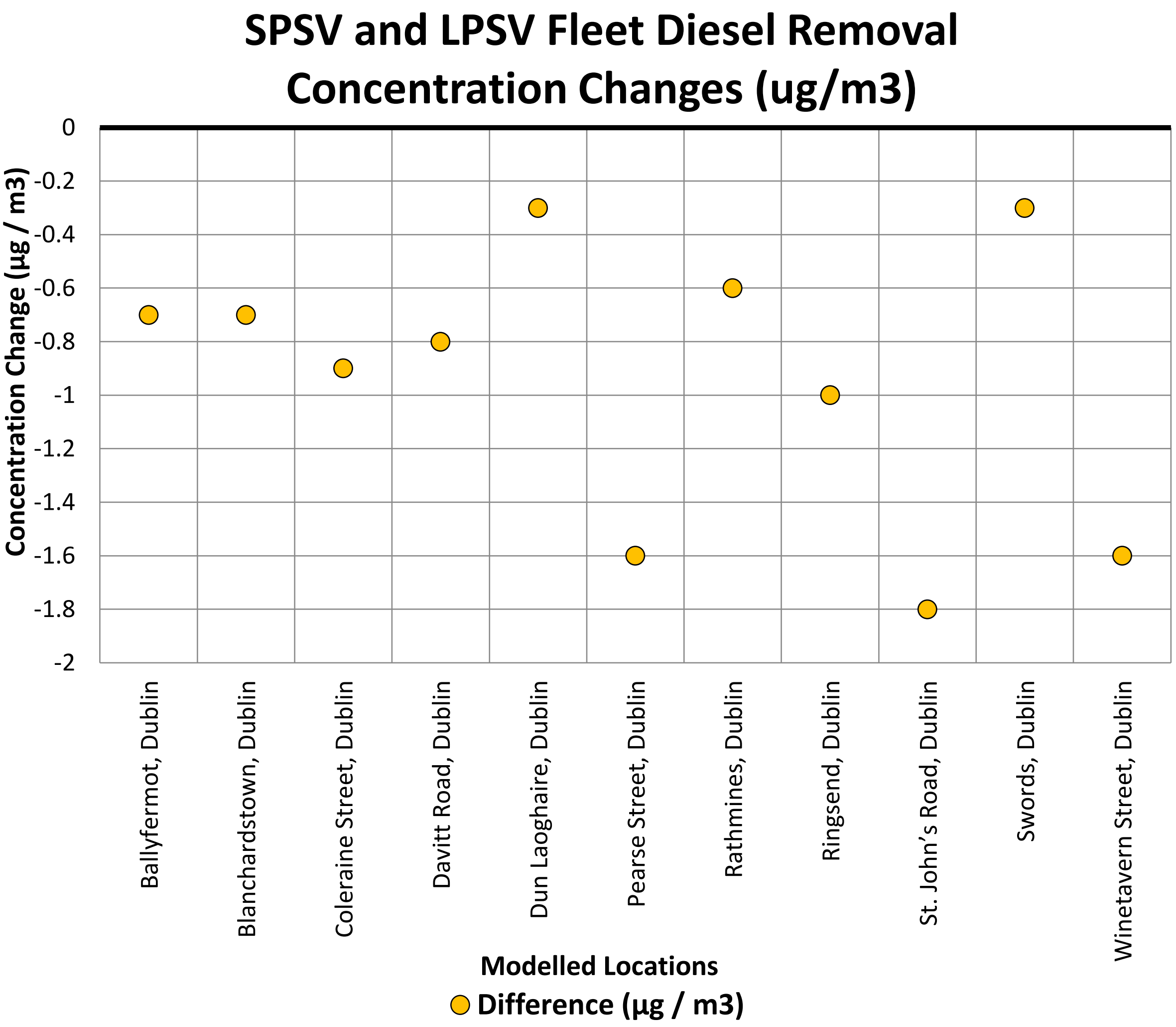


Figure 6.12: Small Public Service Vehicle and Large Public Service Vehicle Fleet Diesel Removal Concentration Change at Modelled Locations

6.2.3. Conclusions

This analysis evaluated the effects of removing diesel fuelled vehicles from the SPSV and LPSV fleets and replacing these vehicles with electric powered vehicles. This mitigation measure focused on determining the changes in NO_2 concentrations due to the changes in the fleet breakdown for SPSVs and LPSVs. The first steps were to determine the average emission rates of an SPSV and LPSV once the fleet was altered to remove diesel powered vehicles and then generate new NO_2 Emission Weightings for the SPSVs and LPSVs that would replace the pre-mitigation measure NO_2 Emission Weightings for these vehicle types.

This mitigation measure aimed to update the SPSV and LPSV fleets, which are predominantly diesel fuelled fleets, to alternative / greener fuel options. The largest changes in concentrations were expected to be in the areas currently experiencing high levels of NO_2 such as Dublin City Centre as the distance travelled by SPSVs and LPSVs are considerably greater in urban areas compared to more suburban or rural areas (Department of Transport, Tourism and Sport & Systra, 2020). Dublin City Centre modelled locations experienced reductions of 1.0 to 1.8 $\mu g / m^3$, which are significant reductions as these modelled locations continue to experience annual mean concentrations close to 40 $\mu g / m^3$, whilst in the Greater Dublin Area, significant reductions were also experienced with reductions between 0.3 and 0.9 $\mu g/m^3$.

6.3. Cork Ring Road

The transport expenditure by the Irish Government is well below the average of EU countries as described in Section 2.4.2. Increasing transport expenditure to develop and upgrade the existing transport network is essential to improve the efficiency of the network. This in turn would improve the efficiency of the public transport service and ensure the network can withstand the increasing number of people using the network on a daily basis. The construction of new routes which bypass urban areas would aim to provide alternate routes for road network users reducing the congestion in a particular location as well as reducing the overall distance travelled by vehicles within built up areas or areas experiencing significant levels of pollution. This mitigation strategy was selected as it has the potential to change traffic flows across multiple routes within a greater urban area and reduce vehicle numbers travelling directly through a city centre.

The Galway Ring Road project described in Section 2.4.3.1 identifies the difficulties that are typically associated with the planning of a ring road in Ireland and the important function that a ring road serves in reducing congestion and air pollution in town / city centres. The focus of this analysis will be on Cork City and the proposed ring road to the north of the city extending from the N22/N40 route at Ballincollig, west of the city to the M8 junction north east of the city (north of Glanmire and the Dunkettle Interchange), shown in Figure 6.14. As of 2016, the population of Cork City was 125 700 and the Cork County population was 417 200 (Central Statistics Office, 2017). Cork was selected for the ring road mitigation scenario as it is the second largest city in Ireland and route options for traffic within Cork City are constrained, in particular for traffic travelling north / northeast to and from areas south and west of the city. There are 4 crossings in the city centre currently (including one northbound one-way flow and one southbound one-way flow) and a southern ring road which crosses the River Lee to the east of the city. There are a number of minor route crossings to the west of the city but these require significant diversions and increases in vehicle kilometres travelled along minor routes for traffic travelling north / northeast to and from areas south and west of the city. Modelled locations considered for this analysis are shown in Section 6.3.1.1 and Figure 6.15. These modelled locations included the EPA monitoring station locations in Cork City and a number of additional locations which were of interest in this analysis such as the intersections of the existing major routes into the city with the new ring road and another location which is located on the city side of the ring road and is in close proximity to the existing main corridor around the south side of the city. These locations would identify impacts on the areas close to the new ring road and the effects of the new ring road on existing heavily trafficked routes within and around the city.

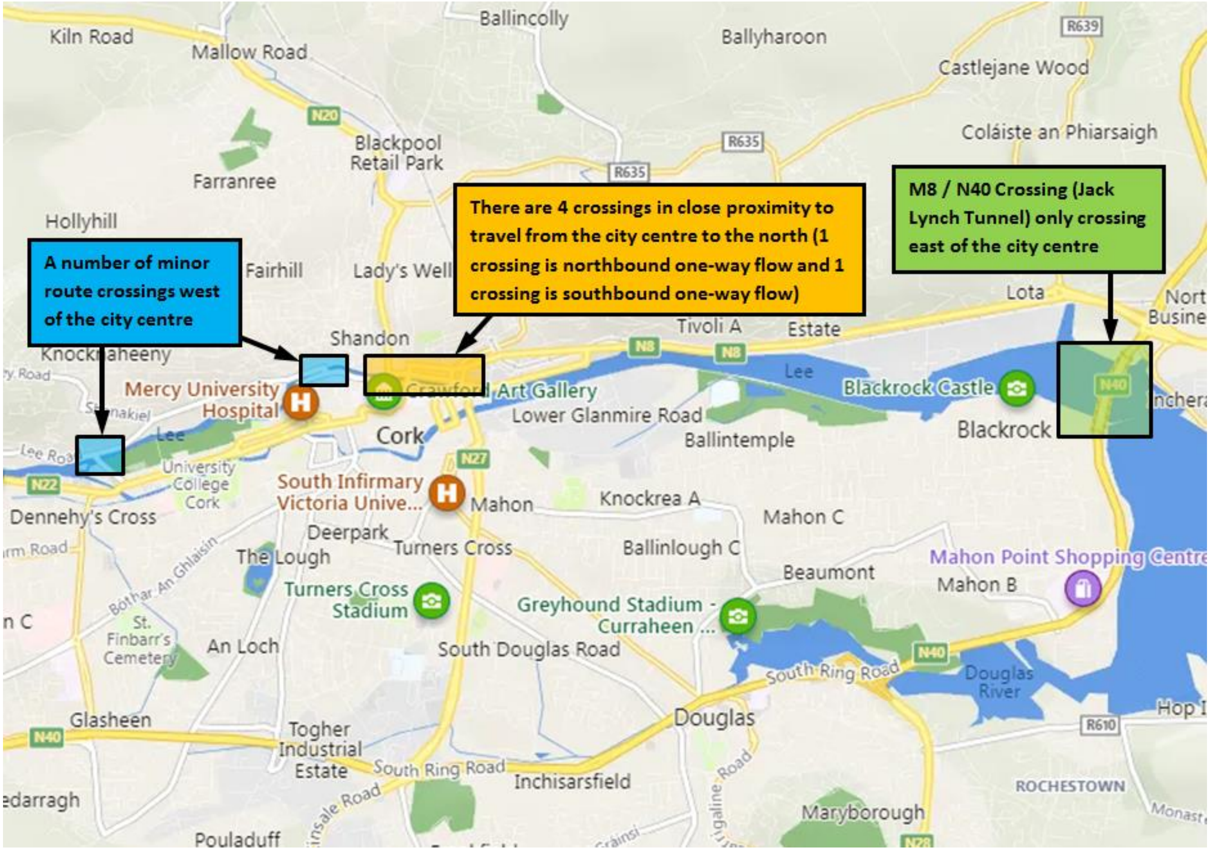


Figure 6.13: Existing Crossings Over River Lee in Cork (Bing Maps, 2022)

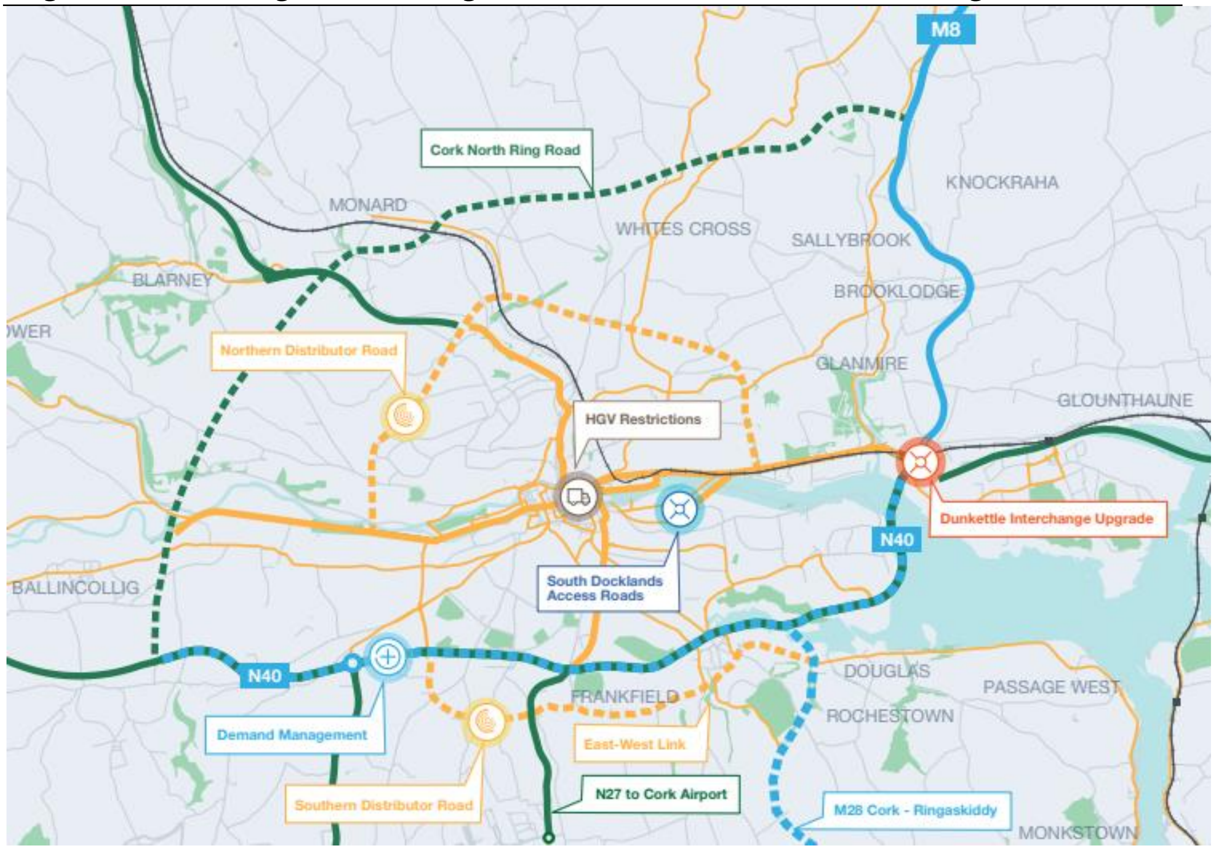


Figure 6.14: Cork Ring Road Alignment (National Transport Authority, 2020)

6.3.1. Methodology and Data

6.3.1.1. Inverse Distance Weighted Vehicle Kilometres Travelled Data

In this section the steps taken to determine the IDWVKT within each of the directional sectors at all modelled locations are described and details of the data source are provided. The changes in flows from the Do-Minimum (no ring road) and Cork Ring Road scenarios for each vehicle type and AADT across all routes are mapped to determine the locations which contribute to changes in IDWVKT. The methodology used to analyse the data was the same as that used for the IDWVKT data in the WS-LUR model development, described in Section 3.3.4.

Traffic flow data for the Cork Ring Road scenario was based on outputs from the National Transport Authority's South Region Model which contains routes of all standards (motorway, national, rural, local, unclassified routes) within Munster. All EPA monitoring stations located within the confines of the South Region of the NTA model were included in the set of locations where NO_2 concentrations were modelled in this analysis. A number of additional locations were also included in the analysis as the number of EPA monitoring stations located close to the new ring road alignment were limited, as shown in Figure 6.15 to Figure 6.19 which show the flow changes in each vehicle type category (AADT, Car / Taxi, LGV, HGV and LPSV) for every route in the NTA south region model due to the introduction of the proposed Ring Road. Figure 6.15 identifies the changes in AADT flows. Figure 6.16 identifies the changes in car / taxi flows. Figure 6.17 identifies changes in LGV flows. Figure 6.18 identifies changes in HGV flows and Figure 6.19 identifies the changes in LPSV flows. Four locations, one at each of the major interchanges between the existing road network and the new Cork Ring Road (N22 / R608 Junction, N20 Junction, R614 Ballyhooly New / Old Mallow Road Junction and the M8 Junction) were identified as areas where considerable traffic flows changes could occur and would be in close proximity to the new route as well as existing major routes into the city. This provided the opportunity to determine particular routes which could potentially contribute to changes in the ambient NO_2 concentrations. Two additional locations (N40 South Ring / N71 Bandon Junction and Passage West) were identified as they were in close proximity to corridors into the city prior to the ring road scenario being implemented and the impact of the ring road at these locations would need to be quantified. Quantifying the changes in ambient NO_2 concentrations at these key locations would confirm that the positive effects in air quality at one location would not outweigh potential negative concentration changes elsewhere.

The NTA model results show that the new ring road had a positive influence on vehicle flows on the major routes from the north into Cork City, with reductions greater than 10% in AADT experienced on sections of these major routes (N20, N8/M8, R616/R615/R635 and the R614/Old Mallow Road) on the city side of the ring road and through the city centre, as shown in Figure 6.15. The AADT on the N22/R608 (corridor from the west of Cork), in close proximity to the ring road interchange, increased by over 10% indicating that traffic which previously travelled through the city (traffic from the north and east) to cross the River Lee, may use the proposed ring road to travel to Ballincollig and west of the city. Similar trends were experienced in the car/taxi flows, as shown in Figure 6.16.

Contrasting trends were experienced in the LGV fleet on some major routes (N20 and M8) into the city, with the flows increasing by 10% on sections of the routes on the city side of the ring road, as shown by Figure 6.17. Figure 6.18 shows that minor reductions in HGV traffic flows were experienced on the majority of routes inside of the ring road, whilst major routes such as the N20, M8/N8 and N40 South Link Road experienced reductions of greater than 10% in HGV flows, indicating that the ring road was the preferred route for

HGVs to travel from one side of the city to the other. LPSV flows were largely unaffected by the introduction of the ring road as shown in Figure 6.19. This could be due to the prescribed routes for publicly owned LPSVs and in the case of privately owned buses, the origin / destination of the majority of trips could be Cork City centre and therefore the ring road would not alter the routes taken by the bus operators.

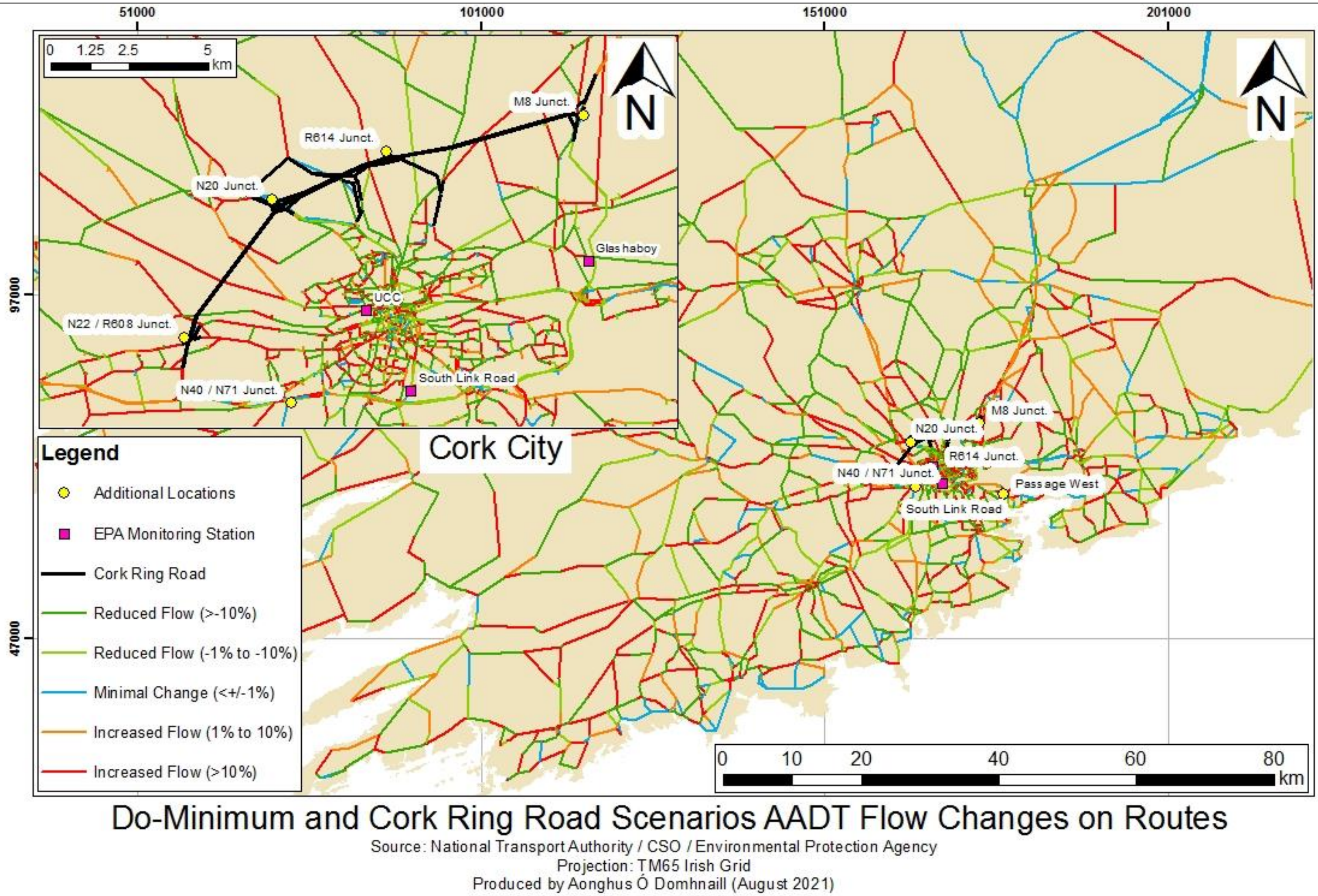


Figure 6.15: Cork Ring Road and Do-Minimum Scenarios AADT Flow Changes on Routes

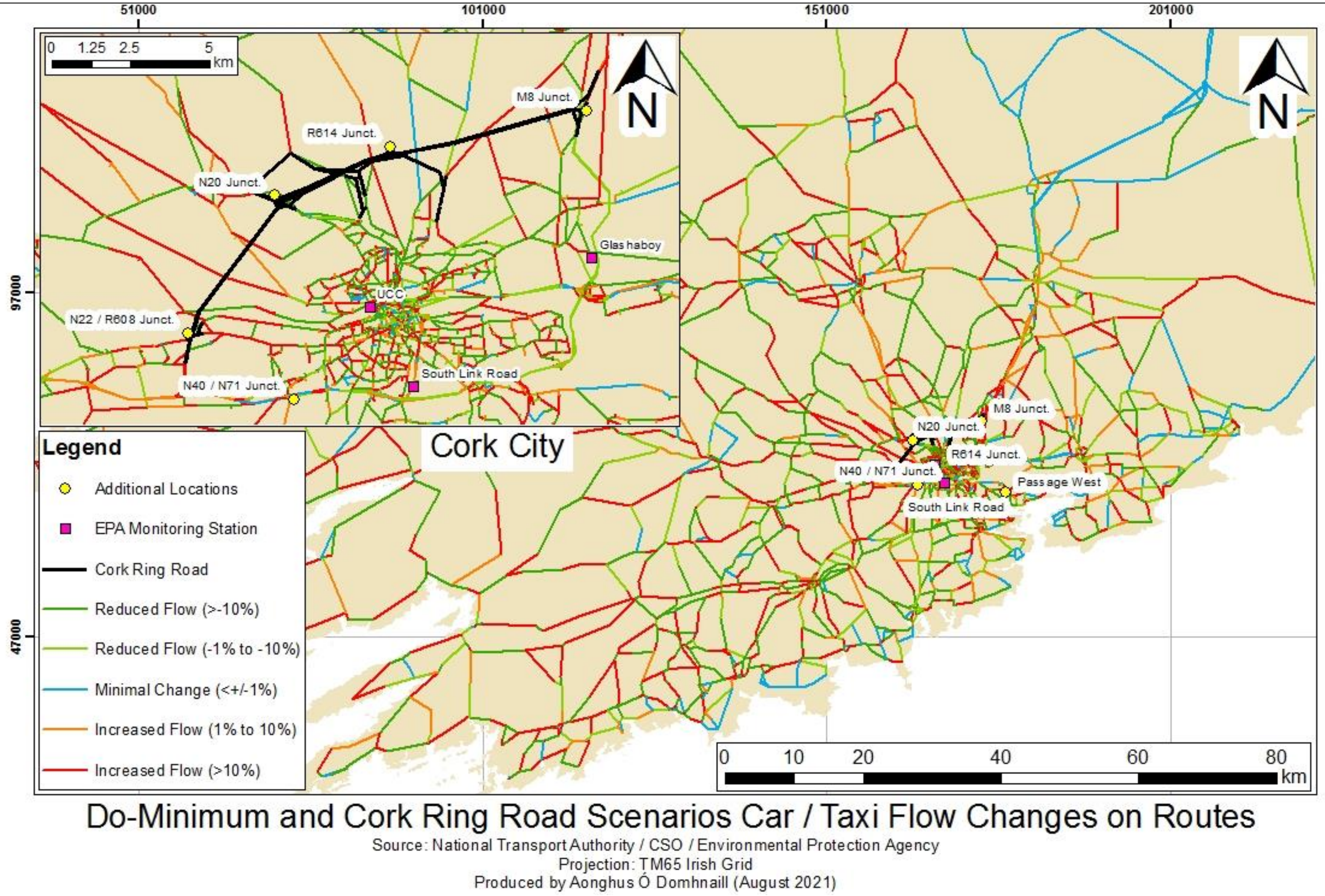


Figure 6.16: Cork Ring Road and Do-Minimum Scenarios Car / Taxi Flow Changes on Routes

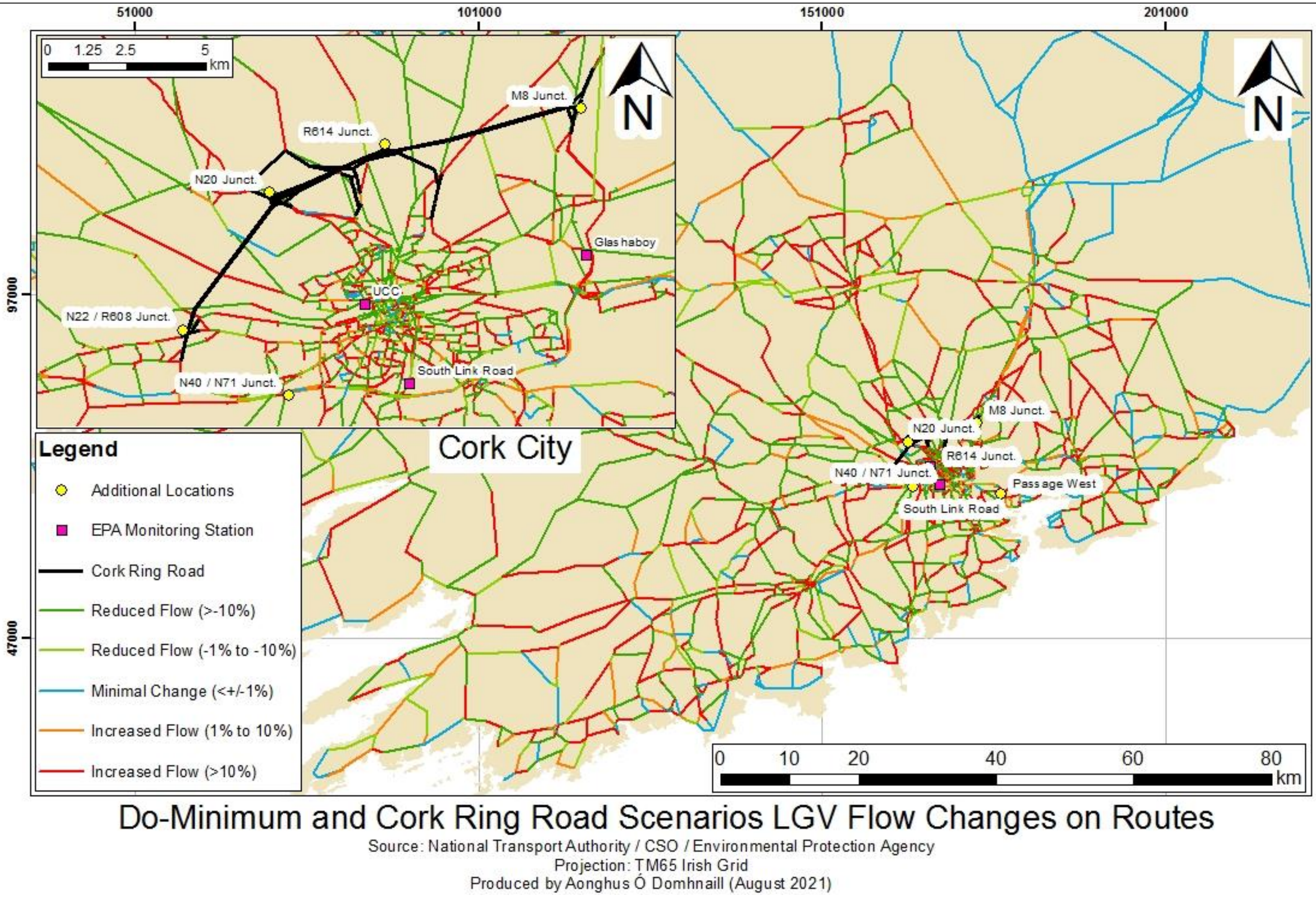


Figure 6.17: Cork Ring Road and Do-Minimum Scenarios LGV Flow Changes on Routes

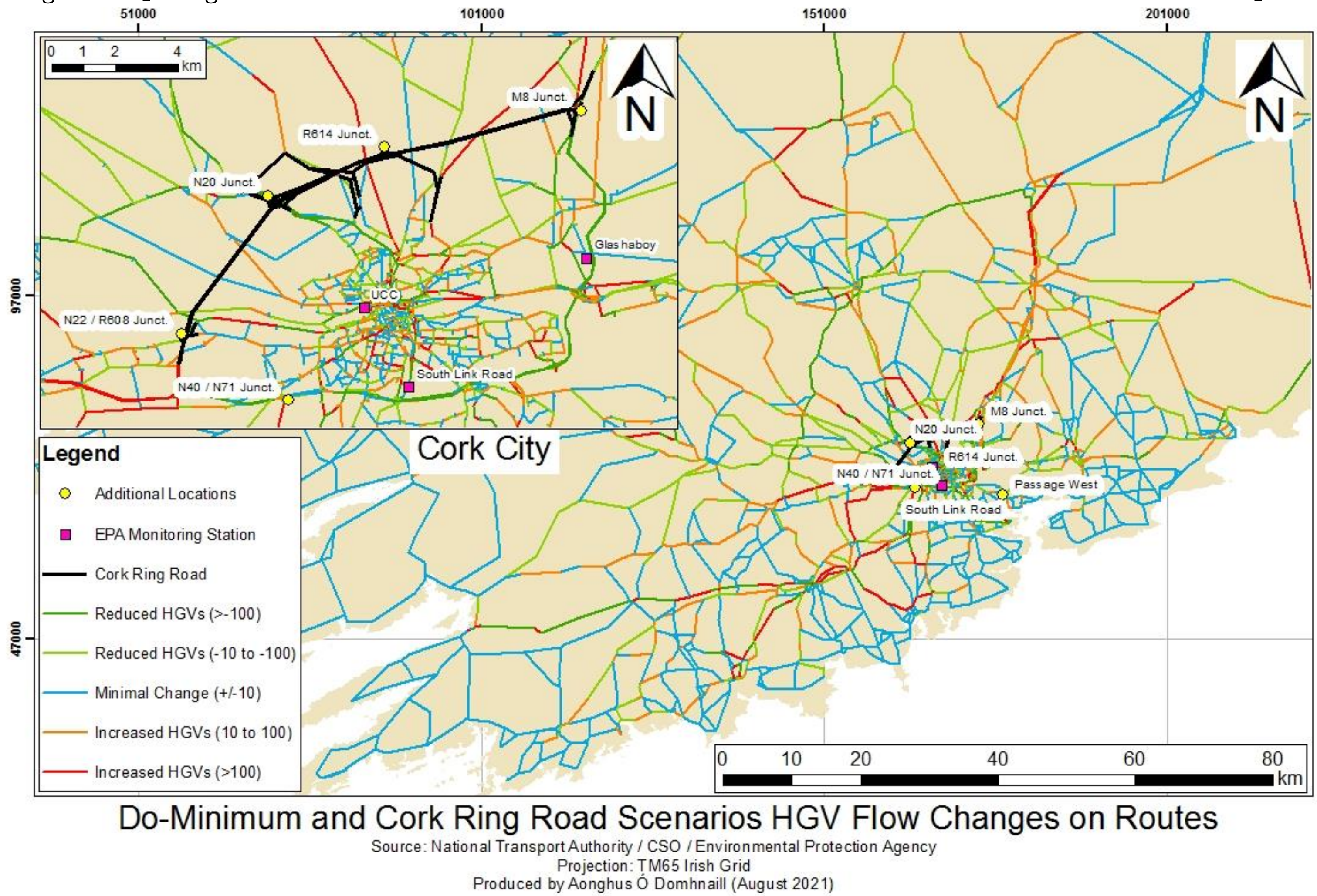


Figure 6.18: Cork Ring Road and Do-Minimum Scenarios HGV Flow Changes on Routes

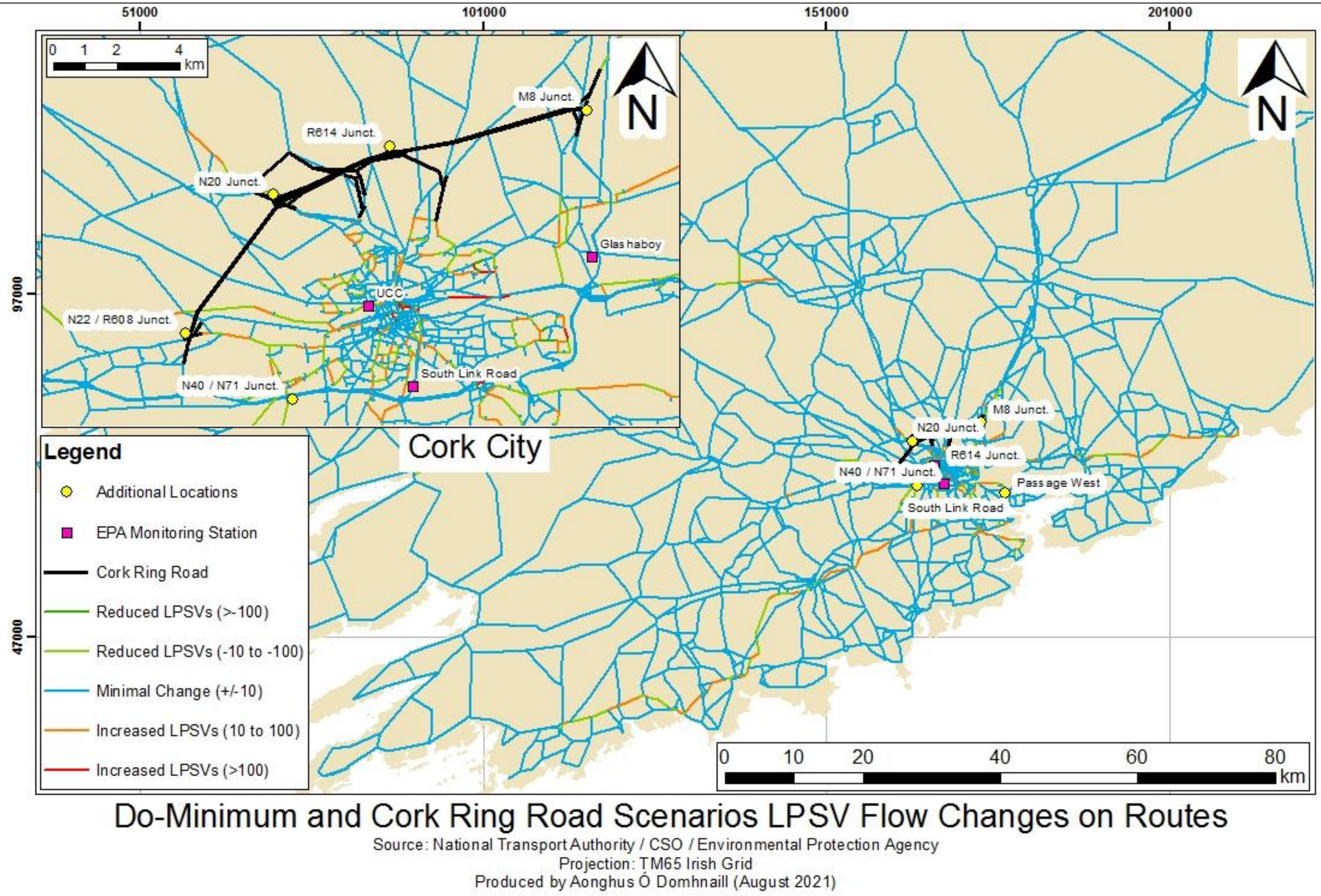


Figure 6.19: Cork Ring Road and Do-Minimum Scenarios LPSV Flow Changes on Routes

Table 6.26 presents the IDWVKT data for all directional sectors at modelled locations. The IDWVKT reduced in the majority of directional sectors for all modelled locations by 0.06% to 25.77%, which equate to reductions in the range of 7 km and 28 208 km. The exceptions were an increase of ~ 18 000 km in the north-west sector at Glashaboy and an increase of ~ 18 000 km and ~ 34 000 km at University College Cork in the north and west sectors respectively. The increase at Glashaboy was mainly due to the change in route taken by the Glanmire population; the data indicating that they are now travelling north towards the ring road rather than travelling west. The increase in the north sector of University College Cork was mainly due to the new traffic flows along the ring road, whilst the increase from the west was mainly due to the increase in traffic along the Old Blarney Road, which the data would suggest was previously travelling towards the N20 but due to the decreased flows on numerous routes within the north of the city has become a more popular option to travel to work, education, etc.

Varying results were noticed at the additional locations. The majority of locations (N22/R608, N20 and R618/Old Mallow Road junction) in close proximity to the new ring road experience increases in IDWVKT in the majority of wind directional sectors due to increased traffic flows from the ring road, as shown in Table 6.26. The M8 junction location had varying results due to the substantial changes in flows on nearby routes with the section of the M8 south of the ring road experiencing reductions in AADT of <10%, but with additional ring road flows experienced to the west of the location. The change of flows from one directional sector to another could have a substantial effect on modelled NO_2 concentrations due to the weighting based on wind direction proportions, particularly if moving to/from the predominant wind directional sector.

At the N40 South Ring / N71 Bandon Junction location, the substantial increase of ~ 44 000 km in IDWVKT in the north sector and minor increases in the northwest and west sectors, shown in Table 6.26, were due to the increase in traffic along the N22 / R608 corridor and its intersection with the new ring road. The changes within all wind direction sectors at the Passage West location were minimal.

Table 6.26: Inverse Distance Weighted Vehicle Kilometres Travelled by Directional Sector for Do-Min (No Ring Road) and Cork Ring Road Scenarios

		INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED							
EPA Monitoring Station	**Scenario**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Glashaboy	Do-Min (No Ring Road)	126 692	37 649	46 582	107 580	191 106	185 541	84 392	40 702
	Cork Ring Road	120 773	38 132	46 931	106 748	185 483	177 856	79 675	57 945
South Link Road	Do-Min (No Ring Road)	393 206	105 901	378 333	71 743	161 169	228 508	240 278	110 406
	Cork Ring Road	371 843	99 729	367 521	70 182	156 526	221 634	233 052	104 209
University College Cork	Do-Min (No Ring Road)	72 850	141 113	240 985	281 727	153 515	160 954	128 069	51 175
	Cork Ring Road	90 638	134 049	223 756	268 544	147 657	156 216	162 954	59 584
N22 / R608 Junction	Do-Min (No Ring Road)	25 090	66 814	127 862	130 023	91 023	97 594	47 368	37 308
	Cork Ring Road	23 139	141 226	155 936	198 011	117 530	109 215	46 860	28 602
N20 Junction	Do-Min (No Ring Road)	5 805	11 706	54 829	130 340	50 735	32 949	77 867	24 375
	Cork Ring Road	17 767	12 483	95 959	143 918	83 487	80 198	99 818	27 188
R614 Ballyhooly New / Old Mallow Road	Do-Min (No Ring Road)	8 458	2 155	50 108	46 604	97 585	33 472	14 144	13 239
	Cork Ring Road	6 278	1 699	89 243	82 957	137 469	108 743	24 764	16 383
M8 Junction	Do-Min (No Ring Road)	65 811	42 503	3 203	2 899	105 704	81 589	17 996	110 410
	Cork Ring Road	90 574	42 670	6 418	3 208	100 718	77 542	49 749	86 473
N40 South Ring / N71 Bandon Junction	Do-Min (No Ring Road)	68 786	438 816	289 113	24 315	69 099	19 556	206 295	203 603
	Cork Ring Road	112 286	410 608	277 439	23 945	68 051	17 640	211 218	209 950
Passage West	Do-Min (No Ring Road)	57 374	20 853	11 538	10 614	17 059	13 711	19 027	62 209
	Cork Ring Road	57 659	20 997	11 531	10 577	17 029	13 598	18 909	61 086

6.3.1.2. Road Density

Road density data for the Do-Minimum and Cork Ring Road scenarios were based on outputs from the National Transport Authority's South Region Model (National Transport Authority, 2021) which contained routes of all standards (motorway, national, rural, local, unclassified routes) within Munster. The methodology used to analyse the data was the same as that used for the road density data in the WS-LUR model development, described in Section 3.3.4. The road density statistics for the majority of locations remained the same between the Do-Minimum and Cork Ring Road scenarios except for locations within 0.25 km of the new ring road, as shown in Table 6.27. The ring road project is a greenfield project, which means there was no existing infrastructure within the ring road alignment. Therefore, road density around the EPA monitoring station locations and N40/N71 Junction and Passage West locations were unaffected whilst a number of the additional locations (such as N22/R608, N20 Junction, R614/Old Mallow Road Junction and M8 Junction) had increased road density values in the Cork Ring Road scenario.

Table 6.27: Road Density by Directional Sector for Do-Min (No Ring Road) and Cork Ring Road Scenarios

Monitoring Station	Modelled Scenario	N	NE	E	SE	S	SW	W	NW
Glashaboy	Do-Min (No Ring Road)	0	0	0	0	0	0	0	0
	Cork Ring Road	0	0	0	0	0	0	0	0
South Link Road	Do-Min (No Ring Road)	3 372	874	0	0	0	2 361	0	1 868
	Cork Ring Road	3 372	874	0	0	0	2 361	0	1 868
University College Cork	Do-Min (No Ring Road)	2 261	1 699	3 111	0	0	0	2 289	3 177
	Cork Ring Road	2 261	1 699	3 111	0	0	0	2 289	3 177
N22 / R608 Junction	Do-Min (No Ring Road)	0	0	782	809	1 379	0	0	0
	Cork Ring Road	0	0	2 910	5 882	1 570	0	0	0
N20 Junction	Do-Min (No Ring Road)	0	0	0	0	0	0	0	0
	Cork Ring Road	0	0	0	1 487	1 616	0	0	0
R614 Ballyhooly New / Old Mallow Road	Do-Min (No Ring Road)	0	0	0	0	0	0	0	0
	Cork Ring Road	0	0	0	1 272	4 084	1 225	0	0
M8 Junction	Do-Min (No Ring Road)	0	0	0	0	0	697	512	7 409
	Cork Ring Road	1 268	0	0	0	0	0	871	3 922
N40 South Ring / N71 Bandon Junction	Do-Min (No Ring Road)	456	5 003	0	0	0	711	1 498	4 234
	Cork Ring Road	456	5 003	0	0	0	711	1 498	4 234
Passage West	Do-Min (No Ring Road)	0	0	0	1 775	0	0	0	0
	Cork Ring Road	0	0	0	1 775	0	0	0	0

6.3.1.3. Meteorological, Commercial Properties and Land Use Data

This section introduces the sources of data for the variables which were unaffected by the mitigation measure (meteorological, commercial properties and land use) and therefore values were constant for both the Do-Minimum (no ring road) and Cork Ring Road scenarios. The methodology used to analyse the data was the same as that used to develop the background data for the WS-LUR model described in Chapter 3.

The meteorological data used in this analysis was obtained from the Met Éireann historical database and included data for all monitoring stations including offshore stations (Met Éireann, 2020). The construction of a ring road as a mitigation measure only affects the IDWVKT and road density variables within the WS-LUR model and therefore the meteorological conditions (wind speed and wind proportion) were the same for the Do-Minimum (no ring road) and Cork Ring Road scenarios, as shown in Table 6.28 and Table 6.29. Figure 6.20 and Figure 6.21 show the wind roses of the wind speeds and proportions at all modelled locations presented in these tables. The predominant winds were from the south-westerly and westerly wind directions across all locations selected for the Cork Ring Road analysis, with approximately 39% of wind measurements from these directions and the average wind speeds in the directional sectors ranged from 3.75 to 5.74 m/s. The methodology used to analyse the data was the same as that used for the meteorological data in the WS-LUR model development, described in Section 3.3.1.

Table 6.28: Wind Speed by Directional Sector for Do-Minimum (No Ring Road) and Cork Ring Road Scenarios

WIND SPEED (m/s)								
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Glashaboy	4.41	3.88	4.91	5.51	5.35	5.33	5.43	5.11
South Link Road	4.55	4.13	5.02	5.54	5.16	5.22	5.35	5.07
University College Cork	4.49	4.03	4.95	5.50	5.19	5.22	5.34	5.06
N22 / R608 Junction	4.46	4.00	4.92	5.48	5.18	5.20	5.33	5.03
N20 Junction	4.38	3.90	4.83	5.42	5.17	5.17	5.30	4.99
R614 Ballyhooly New / Old Mallow Road	4.34	3.85	4.78	5.39	5.18	5.16	5.29	4.97
M8 Junction	4.27	3.75	4.71	5.35	5.22	5.17	5.30	4.96
N40 South Ring / N71 Bandon Junction	4.55	4.13	5.01	5.52	5.13	5.19	5.32	5.05
Passage West	4.54	3.94	5.14	5.74	5.70	5.66	5.70	5.38

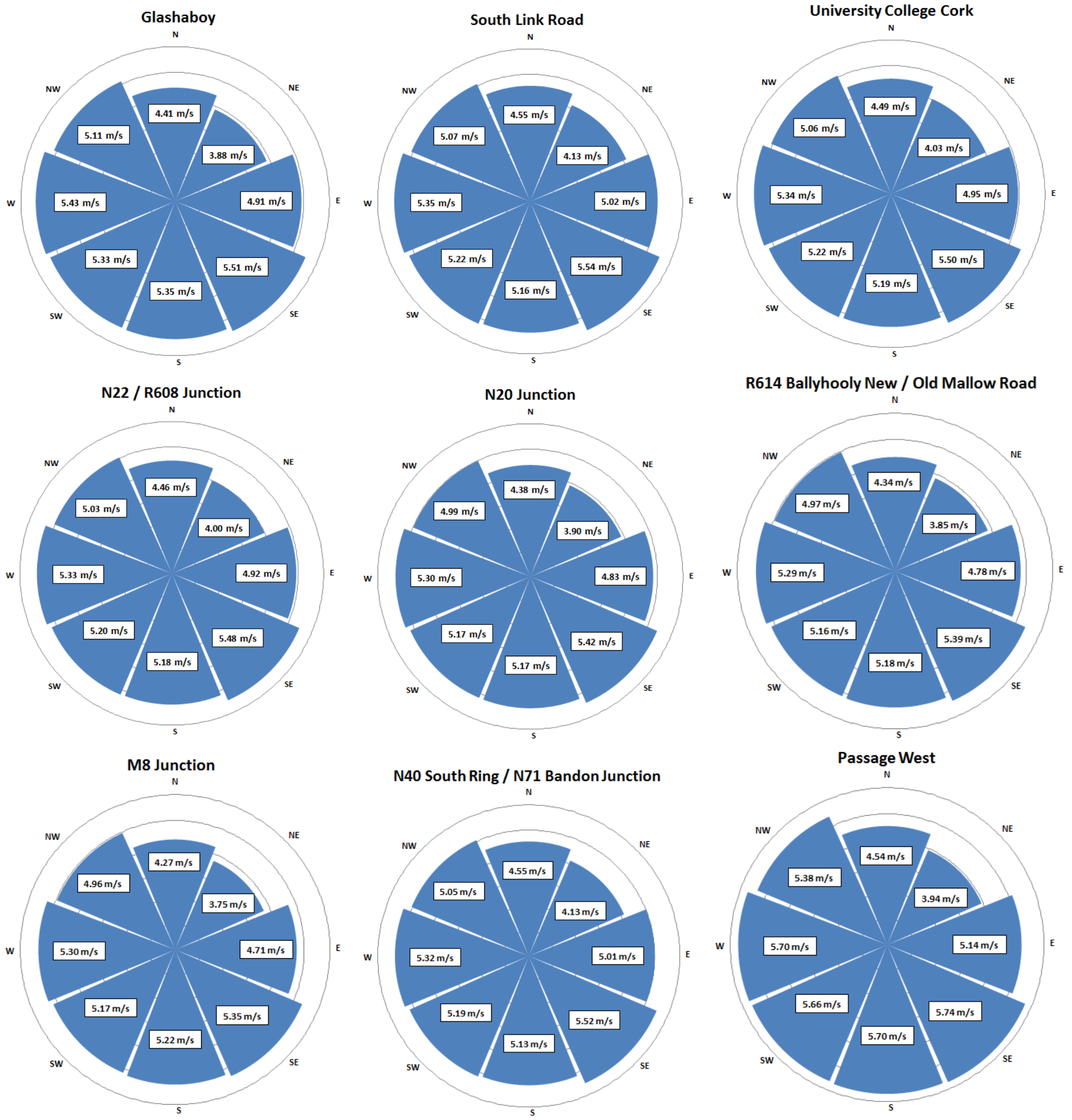
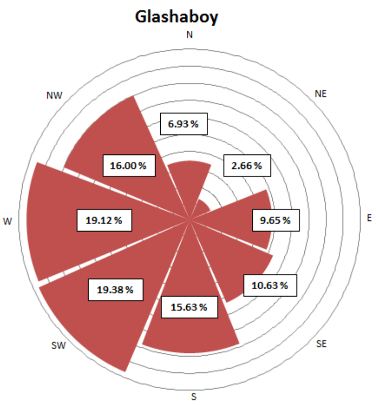
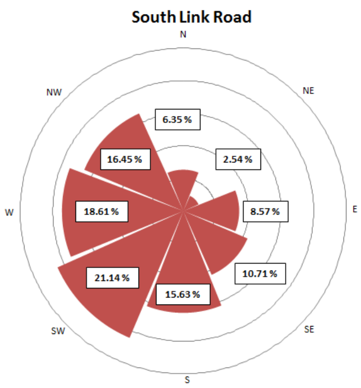


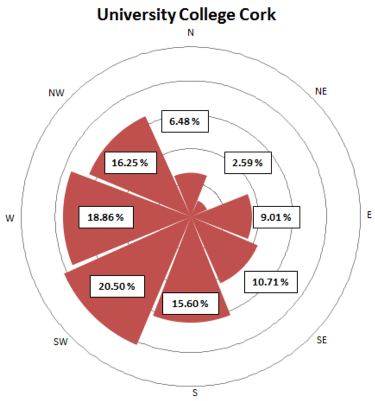
Figure 6.20: Wind Speed Roses for Do-Minimum (No Ring Road) and Cork Ring Road Scenarios

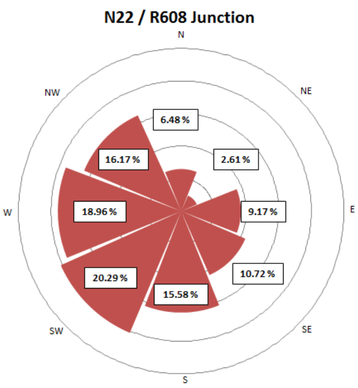
Table 6.29: Wind Proportions by Directional Sector for Do-Minimum (No Ring Road) and Cork Ring Road Scenarios

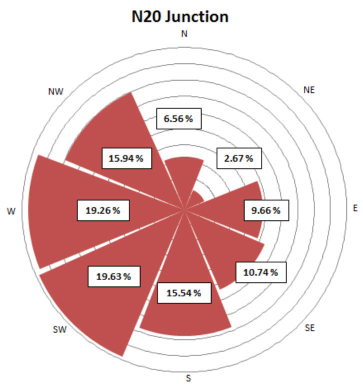
WIND PROPORTION (%)								
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Glashaboy	6.93	2.66	9.65	10.63	15.63	19.38	19.12	16.00
South Link Road	6.35	2.54	8.57	10.71	15.63	21.14	18.61	16.45
University College Cork	6.48	2.59	9.01	10.71	15.60	20.50	18.86	16.25
N22 / R608 Junction	6.48	2.61	9.17	10.72	15.58	20.29	18.96	16.17
N20 Junction	6.56	2.67	9.66	10.74	15.54	19.63	19.26	15.94
R614 Ballyhooly New / Old Mallow Road	6.63	2.70	9.93	10.74	15.52	19.24	19.43	15.82
M8 Junction	6.79	2.76	10.40	10.73	15.49	18.53	19.69	15.61
N40 South Ring / N71 Bandon Junction	6.28	2.54	8.56	10.74	15.61	21.20	18.62	16.45
Passage West	7.58	2.59	9.22	10.40	15.83	19.50	18.59	16.30

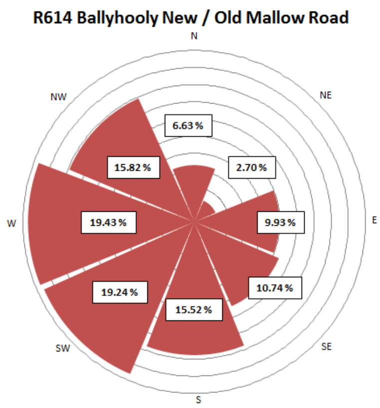












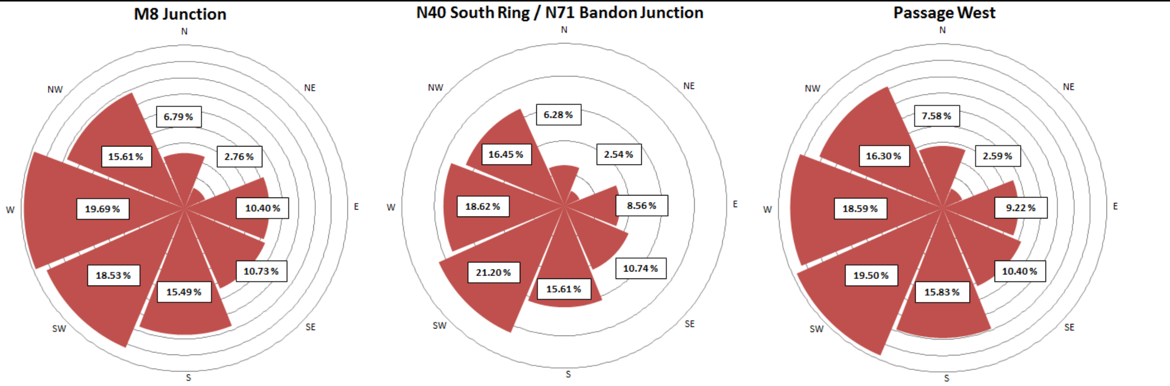


Figure 6.21: Wind Proportion Roses for Do-Minimum (No Ring Road) and Cork Ring Road Scenarios

The commercial properties data was sourced from An Post / Geodirectory and represented 2019 conditions (GeoDirectory, 2020). The construction of a ring road as a mitigation measure only affects the IDWVKT variable within the WS-LUR model and therefore the commercial property numbers were the same for the Do-Minimum (no ring road) and Cork Ring Road scenarios, as shown in Table 6.30. The methodology used to analyse the data was the same as that used for the commercial properties data in the WS-LUR model development, described in Section 3.3.3.

Table 6.30: Commercial Properties by Directional Sector for Do-Minimum (No Ring Road) and Cork Ring Road Scenarios

Monitoring Station	N	NE	E	SE	S	SW	W	NW
Glashaboy	1	2	1	1	4	2	16	16
South Link Road	32	38	3	0	6	95	73	27
University College Cork	45	268	1507	741	98	28	67	17
N22 / R608 Junction	4	2	6	2	5	65	7	0
N20 Junction	4	3	2	2	0	0	0	1
R614 Ballyhooly New / Old Mallow Road	1	3	0	1	2	1	3	1
M8 Junction	4	0	0	2	0	3	0	1
N40 South Ring / N71 Bandon Junction	90	36	110	0	3	21	3	33
Passage West	73	3	2	0	1	2	5	1

The land use data was sourced from the European Environment Agency / Copernicus database (European Environment Agency & Copernicus, 2020) and was the same data used to represent the pre-COVID conditions in the COVID analysis, as described in Section 5.2.5. The construction of a ring road as a mitigation measure only affects the IDWVKT variable within the WS-LUR model and therefore the meteorological conditions (wind speed and wind proportion) were the same for the Do-Minimum (no ring road) and Cork Ring Road scenarios, as shown in Table 6.31. The methodology used to analyse the data was the same as that used for the land use data in the WS-LUR model development, described in Section 3.3.2.

Table 6.31: Natutral / Agricultural Land Use by Directional Sector for Do-Min (No Ring Road) and Cork Ring Road Scenarios

Monitoring Station	N	NE	E	SE	S	SW	W	NW
Glashaboy	221 523	382 630	362 491	241 661	181 246	302 076	271 869	221 523
South Link Road	0*	0*	0*	0*	0*	0*	0*	0*
University College Cork	0*	0*	0*	0*	0*	0*	0*	0*
N22 / R608 Junction	342 353	243 099	20 138	308 549	191 315	0*	70 484	355 299
N20 Junction	392 699	392 699	231 592	336 599	392 699	392 699	392 699	392 699
R614 Ballyhooly New / Old Mallow Road	392 699	392 699	382 630	364 649	352 422	392 699	392 699	392 699
M8 Junction	221 523	317 899	322 215	392 699	392 699	168 300	342 353	364 649
N40 South Ring / N71 Bandon Junction	10 069	9 350	30 208	299 199	382 630	345 949	100 692	9 350
Passage West	40 277	102 850	231 592	28 050	151 038	336 599	342 353	37 400

* No natural / agricultural land use within directional sector

6.3.1.4. Methodology and Data Summary

The statistics generated as part of the data analyses described between Sections 6.3.1.1 and 6.3.1.3 for the Cork Ring Road scenario were collated and input into the WS-LUR model. The manual entry approach was selected within the model and the statistics for each of the predictor variables were input into the respective sections (Section A for meteorological data; Section B for land use data; Section C for commercial properties data and Section D for traffic data (IDWVKT and road density)). The modelled concentrations for the post-mitigation measure scenario were generated for all modelled locations and compared with modelled concentrations for the pre-mitigation measure scenario (2019 conditions), which were calculated previously in the COVID analysis described in Sections 5.2 and 5.3. Results of the concentration changes / comparison are provided in the following section.

6.3.2. Results

Table 6.32 and Figure 6.22 show the concentration changes at EPA monitoring station locations in Cork City and a number of additional locations identified as key locations to determine the impact of the new ring road on air quality in the vicinity of the existing main corridors into the city. Minimal change was experienced at the Glashaboy station whilst an increase of 0.2 $\mu g / m^3$ in ambient NO_2 concentration was experienced at the University College Cork station.

As discussed above, there was minimal change in the combined IDWVKT across all directional sectors at the University College Cork monitoring station; instead the NO_2 concentration increase at this monitoring station was influenced by a change of traffic from one directional sector to another. Specifically, the combined IDWVKT within southerly and easterly directional sectors (NE, E, SE, S and SW) decreased by the same amount that the combined IDWVKT increased in the north, northwest and west sectors. The ring road, which is located approximately 4 km to the north/northwest/west of the monitoring station, partially contributes to the increase in IDWVKT in these sectors. Moreover, the new ring road also resulted in a change in the routes taken by vehicles to approach their destination, where they previously approached the monitoring station from the city centre side (southerly/easterly directions), they now take routes from the west and north to travel to/past the University College Cork modelled location. These increases in IDWVKT in the predominant wind directional sectors resulted in the minor increase in ambient concentration at this monitoring station.

A decrease of 0.4 μg / m^3 was experienced at the South Link Road station and the changes in traffic flows, particularly along the South Link Road, described in Section 6.3.1.1, were the main cause of this reduction. As expected, the ambient NO_2 concentrations at the N22/R608 Junction, N20 Junction and R614/Old Mallow Road Junction locations in close proximity to the ring road increased by 2.5 μg / m^3, 1.8 μg / m^3 and 3.6 μg / m^3 respectively, due to the additional flows along the ring road as well as the increased road density within 0.25km of these locations, as described in Sections 6.3.1.1. These increases occurred in locations with relatively low modelled concentrations (<6.5 μg / m^3) for the Do-Minimum scenario (prior to the ring road) and therefore did not threaten the exceedance of the Directive 2008/50/EC limit of 40 μg / m^3 at any of the locations. The revised WHO limit of 10 μg / m^3 is of concern throughout Ireland, but after the implementation of the ring road these locations were still below this limit by approximately 1 μg / m^3 to 5.3 μg / m^3. The M8 Junction location experienced a decrease of 1.3 μg / m^3 in ambient NO_2 concentration due to the decrease in traffic travelling southbound through the M8 junction which instead utilised the ring road to travel to the south/west of the city as described in Section 6.3.1.1. The changes in ambient concentration at the Passage West location was minimal due to the limited change in traffic distance travelled at this location. Despite the major increase in traffic north of the N40/N71 Junction location, the ambient NO_2 concentration only increased by 0.1 μg / m^3.

Table 6.32: Cork Ring Road Impacts on Ambient NO_2 Concentrations

Monitoring Station	Modelled Scenario	Modelled Concentration (µg / m^3)	Difference (µg / m^3)
Glashaboy	Do-Min (No Ring Road)	10.7	-0.0
	Cork Ring Road	10.6	
South Link Road	Do-Min (No Ring Road)	25.7	-0.4
	Cork Ring Road	25.3	
University College Cork	Do-Min (No Ring Road)	25.8	0.2
	Cork Ring Road	26.0	
N22 / R608 Junction	Do-Min (No Ring Road)	6.5	2.5
	Cork Ring Road	9.0	
N20 Junction	Do-Min (No Ring Road)	2.9	1.8
	Cork Ring Road	4.7	
R614 Ballyhooly New / Old Mallow Road	Do-Min (No Ring Road)	2.3	3.6
	Cork Ring Road	5.9	
M8 Junction	Do-Min (No Ring Road)	7.3	-1.3
	Cork Ring Road	6.0	
N40 South Ring / N71 Bandon Junction	Do-Min (No Ring Road)	10.2	0.1
	Cork Ring Road	10.3	
Passage West	Do-Min (No Ring Road)	4.0	-0.0
	Cork Ring Road	4.0	

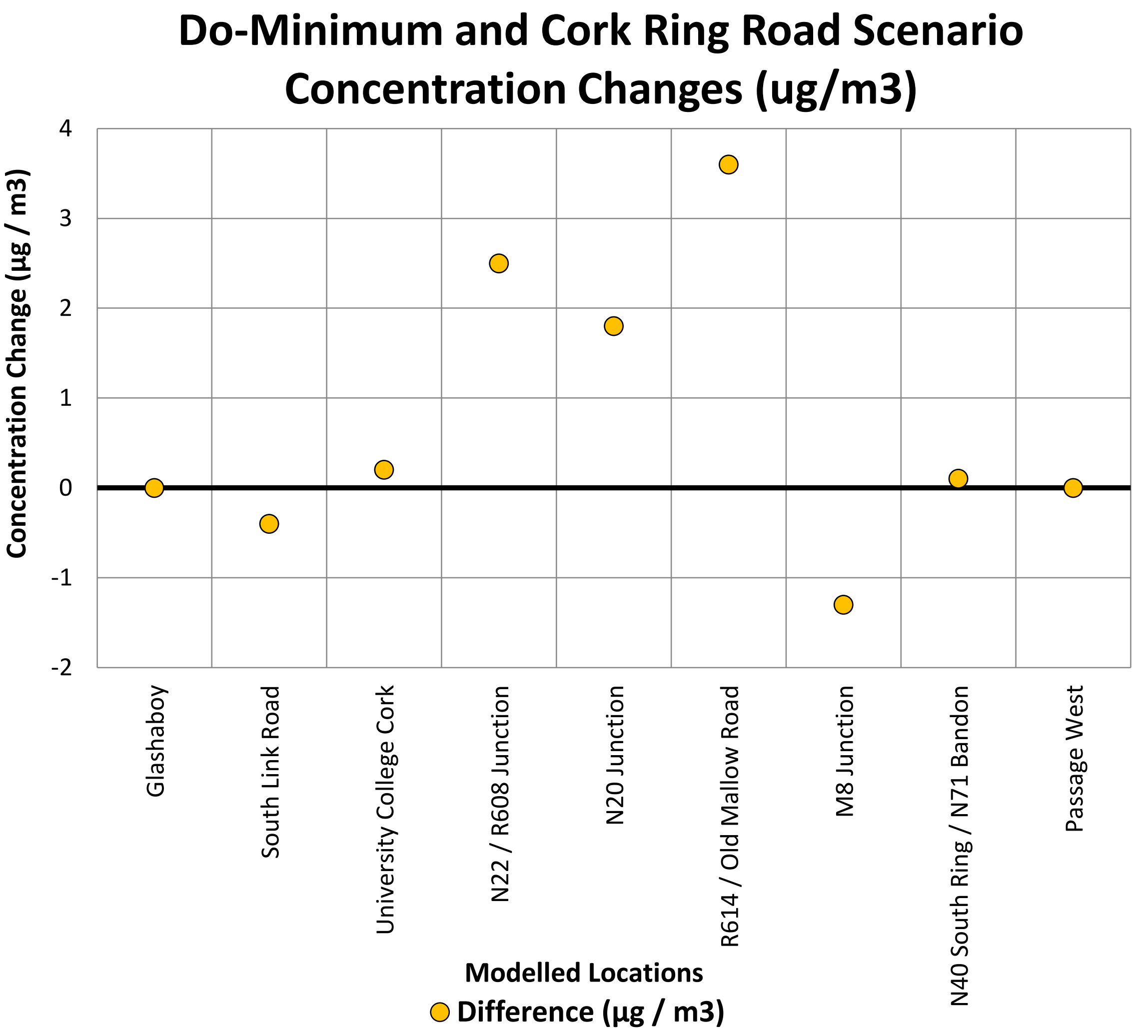


Figure 6.22: Do-Minimum and Cork Ring Road Concentration Change at Modelled Locations

6.3.3. Conclusions

This analysis evaluated the air quality effects of constructing a ring road to the north of Cork City. This mitigation measure focused on determining changes in NO_2 concentrations in Cork City due to the addition of the proposed ring road and the associated effects on traffic flows on all routes in the southwest of Munster.

Locations were identified along the ring road and its intersection with existing major routes into Cork City to determine potential changes in NO_2 concentrations at these locations. Increases of 2.5, 1.8 and 3.6 $\mu g/m^3$ were experienced at the N22/R608, N20 and R614 junctions respectively. The concentration at the M8 junction with the ring road experienced reductions of 1.3 $\mu g/m^3$ in comparison to the Do-Minimum (no ring road) scenario which highlights that a large proportion of road users switched routes once the ring road was constructed, from the route east and south of the city (N40 / M8) to the new ring road north and west of the city. Minor increases (approximately 0.1 to 0.2 μg/m^3) were experienced in areas to the north and west of the city which were in close proximity to the ring road (less than 5km), such as the N40/N71 junction and University College Cork locations. These increases were due to the location of the ring road relative to the monitoring sites, which was within the predominant wind directional sector, and local increases in IDWVKT due to the ring road. Reductions of approximately 0.4 μg/m^3 were experienced to the south / east of the city, such as at the South Link Road location, which benefitted from changes in route selection due to the inclusion of the ring road.

6.4. Dublin Low Emission Zone (LEZ)

Section 2.4.3.2 identified the significant improvements in air quality that can be achieved by introducing a charge on particular vehicles entering a zone. Improvements in air quality due to the introduction of and Low Emission Zone (LEZ) were not limited to the area within the zone with significant improvements also experienced near the border of the zone. A mitigation measure such as an LEZ is capable of reducing pollution levels across a wide region and can be used to encourage people to upgrade vehicles to greener fuel options or to upgrade to newer vehicle Euro Classes. This analysis presented in this section focuses on determining the changes in ambient NO_2 concentrations due to implementation of an LEZ scenario in Dublin, using the WS-LUR model described in Chapter 4. The IDWVKT values for this scenario were calculated from traffic flow data contained within the output of an LEZ scenario modelled by the National Transport Authority using their National Transport East Region Model (National Transport Authority, 2021). All EPA monitoring stations located within the confines of the East Region of the NTA model were considered in this analysis. The LEZ introduced a €10.00 daily charge on any vehicle travelling into the zone shown in Figure 6.23. This was a similar charge to that currently applied to non-compliant vehicles entering the London LEZ, which as mentioned above was £12.50 (Transport for London, 2022). The charge was not applied to any vehicle whose trips originated in the zone.

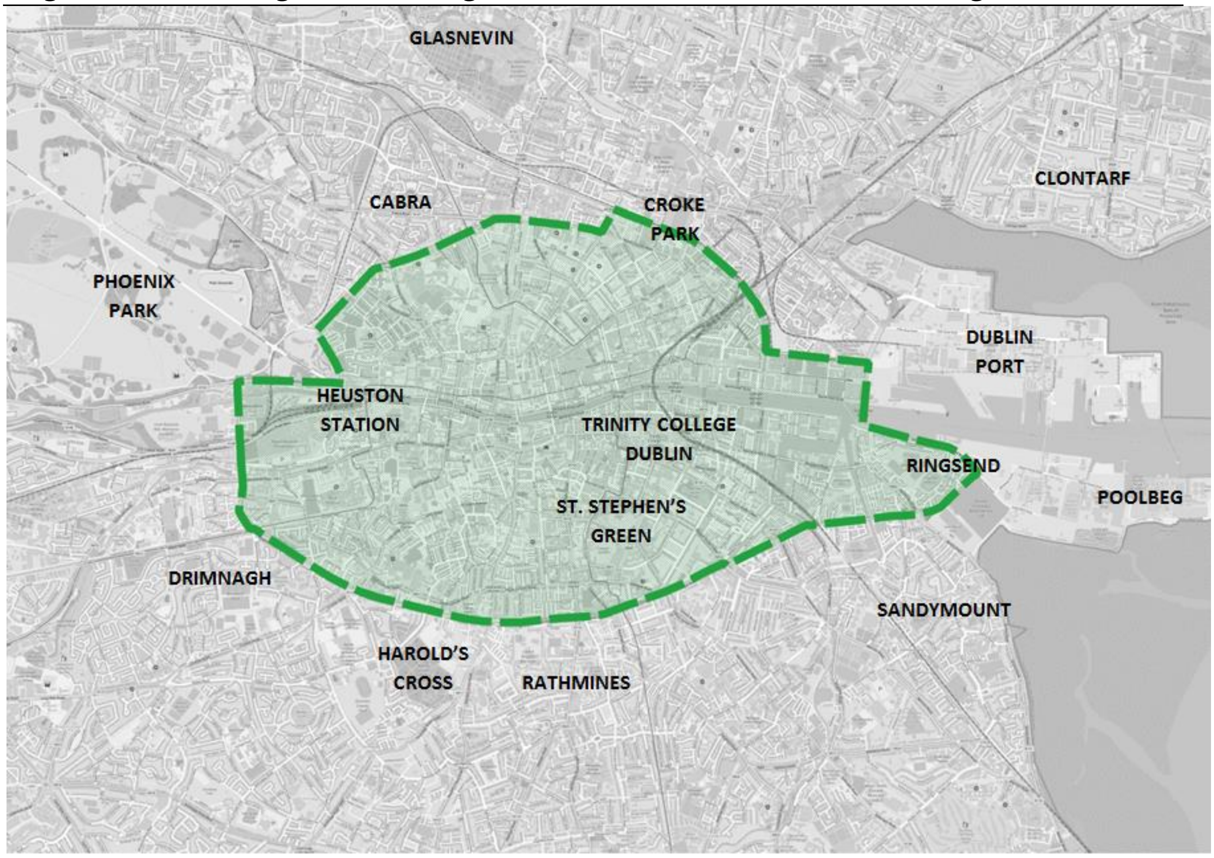


Figure 6.23: East Region Model Dublin LEZ Boundary (National Transport Authority and Systra, 2021)

All EPA monitoring station locations within the confines of the East Region of the NTA model were considered in this analysis and are mapped in Section 6.4.1.1. These locations were ideal for this scenario as they provided a wide range of locations which would be of interest in this mitigation scenario. A number of the locations were located centrally within the LEZ (e.g. Pearse Street, Winetavern Street, etc.) and would provide a good insight into the full effects of the LEZ in the city centre. A number of the locations were on the LEZ boundary (e.g. Davitt Road, Ringsend, etc.) and would identify if the LEZ impacted the population located just within / outside of the LEZ boundary. Locations in close proximity to heavily trafficked routes within the Greater Dublin Area, such as Blanchardstown and Dun Laoghaire, would identify the effects of the LEZ in the wider region surrounding the LEZ. The effects of the LEZ on commuter towns and rural regions in the surrounding counties were also of interest and locations such as Navan, Emo Court and Newbridge would provide an insight into the effects in these areas.

6.4.1. Methodology and Data

6.4.1.1. Inverse Distance Weighted Vehicle Kilometres Travelled Data

In this section the steps taken to determine the IDWVKT within each of the directional sectors at all modelled locations are described and details of the data source are provided. The changes in flows from the pre- and post-mitigation measure scenarios for each vehicle type and AADT across all routes are mapped to determine the locations which contribute to changes in IDWVKT. The methodology used to analyse the data was the same as that used for the IDWVKT and road density data in the WS-LUR model development, described in Section 3.3.4.

Traffic flow data for the Dublin Low Emission Zone (LEZ) scenario was based on outputs from the National Transport Authority's East Region Model which contains routes of all standards (motorway, national, rural, local, unclassified routes) within Leinster. The model was developed for a future year (2030) and therefore would include growth rates for future traffic flows in comparison to the 2019 modelled flows (Transport Infrastructure Ireland, 2021). Table 6.33 identifies the Annual Growth Rates for links as specified by Transport Infrastructure Ireland's Project Appraisal Guidelines for National Roads Unit 5.3 – Travel Demand Projections (Transport Infrastructure Ireland, 2021) for Light Vehicles (LV) (Passenger Cars and LCVs) and for Heavy Vehicles (HV) (HDVs) and the expected increase in both the LV and HV categories between 2019 and 2030 are also shown.

Table 6.33: LV and HV Annual and 2019 – 2030 Growth Rates

	LV Annual Growth Rate	LV 2019 – 2030 Growth Rate	HV Annual Growth Rate	HV 2019 – 2030 Growth Rate
Dublin City	1.016	21.27%	1.03	41.75%
Co. Dublin	1.018	23.87%	1.032	45.43%
Co. Kildare	1.02	26.38%	1.038	56.09%
Co. Meath	1.017	22.85%	1.037	53.76%
Co. Wicklow	1.016	20.56%	1.038	55.91%
Co. Louth	1.015	19.28%	1.036	53.40%
Co. Carlow	1.013	17.18%	1.032	46.61%
Co. Kilkenny	1.012	15.94%	1.027	37.35%
Co. Laois	1.015	19.14%	1.028	39.29%
Co. Offaly	1.012	15.12%	1.032	46.44%
Co. Westmeath	1.016	21.13%	1.032	45.26%
Co. Monaghan	1.012	14.71%	1.025	34.80%
Co. Wexford	1.007	8.47%	1.021	28.48%

Figure 6.24, Figure 6.25, Figure 6.26, Figure 6.27 and Figure 6.28 show the flow changes in each of the vehicle type categories (AADT, Car / Taxi, LGV, HGV and LPSV) for every route in the NTA east region model due to the introduction of an LEZ charge in the Dublin City Centre area shown in Figure 6.23. For a Do-Minimum scenario (no mitigation measure), the predicted future flows within Dublin in 2030 could be approximately 20% greater than the modelled flows in 2019 for light vehicles and approximately 40% greater for heavy vehicles (Transport Infrastructure Ireland, 2021), as shown in Table 6.33. Therefore, the net changes in flows described in this section are impacted by both the general growth in traffic flows as well as the implementation of the LEZ. Wherever the percentage increase in vehicle flows between the pre- and post-mitigation measure scenarios is less than the 2019 - 2030 growth rates shown in Table 6.33, the implementation of an LEZ in the Greater Dublin Area has had a positive impact.

The AADT flows achieved on major routes (such as M1 (Belfast), M3 (Cavan), M4/M6 (Sligo / Galway), M7 (Limerick) and the M50) for 2030 due to the LEZ were >10% lower than the 2019 AADT flows as shown in Figure 6.24. As the majority of vehicles on routes are cars/taxis, this change was also reflected in the Car/Taxi flows as shown in Figure 6.25. Figure 6.26 shows increases of >10% in LGV flows on a significant proportion of routes. This could be due to a number of reasons, such as the increase in traffic flows for future years, but also that commercial vehicles are less affected by LEZs as their trips could be work related (such as deliveries, etc.) requiring them to enter the LEZ irrespective of the fee.

Increases of >10% in HGV flows were experienced on the M50 (approximately 900 HGVs), the main corridors from the M50 into Dublin City Centre (approximately 450 to 600 HGVs), the Dublin Port Tunnel (approximately 3 000 HGVs) and routes along the quays in Dublin City (approximately 200 HGVs) despite the implementation of a LEZ, as shown in Figure 6.27. The scale of the increases is influenced by the comparison with a future year, because as shown in Table 6.33, an increase in HGV traffic of approximately 42% is expected between 2019 and 2030. In the case of the London LEZ, the economic impact of the LEZ on businesses / business owned vehicles was considered to be minimal (Transport for London, 2006). Therefore, predominantly business owned vehicle types such as HGVs may not be impacted as much as predominantly private owned vehicle types such as cars, as they would need to travel through / to the city centre area and Dublin Port. The LPSV flows were largely unaffected outside of the M50 with only increases / decreases in the range of 10 to 100 vehicles per day on the M3, M4/M6 and M7 major routes, as shown in Figure 6.28. In the Greater Dublin Area (within the M50 route), a number of main corridors into the city centre experienced increases of greater than 100 LPSVs in the AADT flows. This again could be due to the predicted increases in flows due to the comparison with a future year, but could also identify a change in the transport mode selected by the population (change towards LPSVs) due to the introduction of the LEZ.

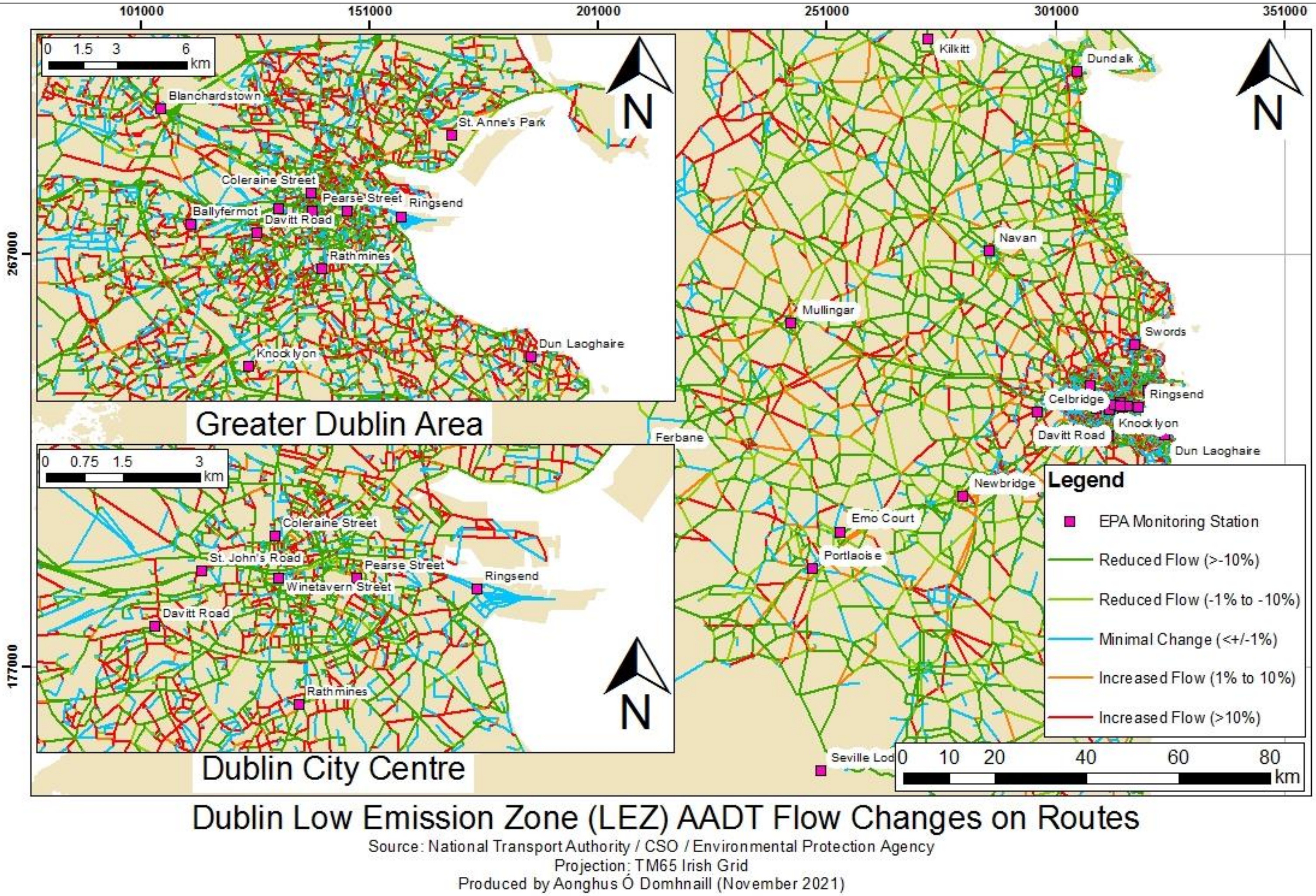


Figure 6.24: Dublin LEZ Scenario AADT Flow Changes on Routes

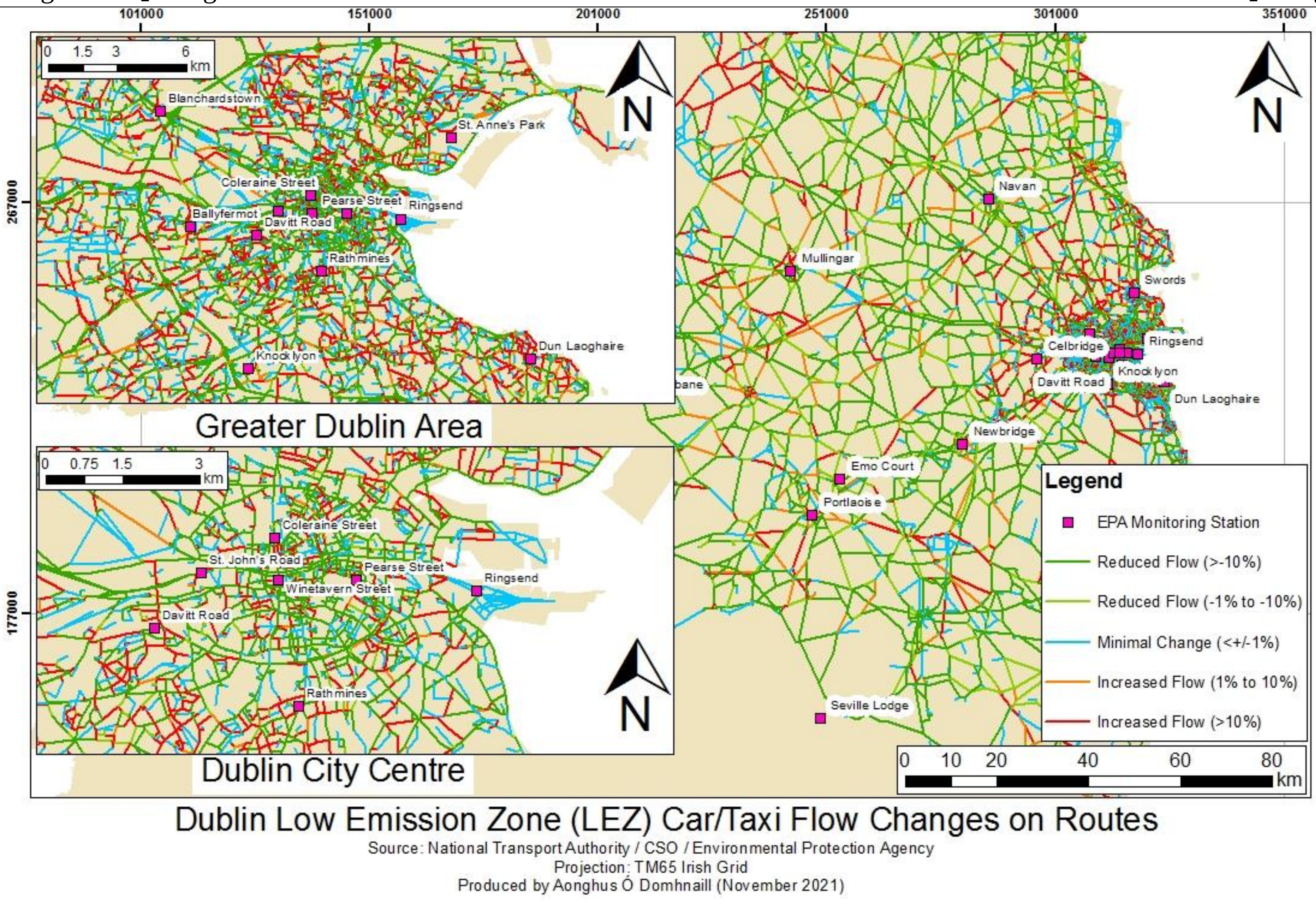


Figure 6.25: Dublin LEZ Scenario Car / Taxi Flow Changes on Routes

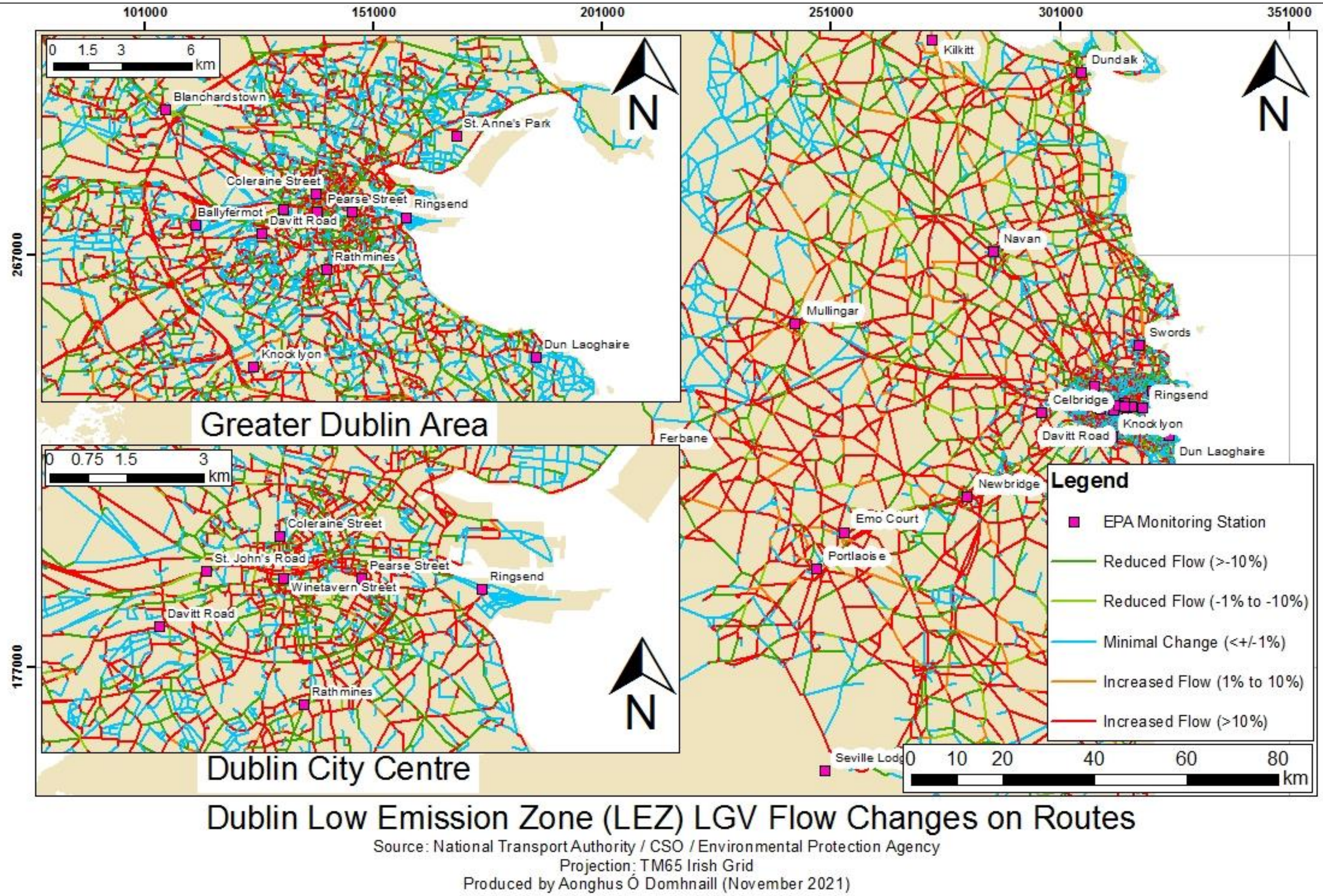


Figure 6.26: Dublin LEZ Scenario LGV Flow Changes on Routes

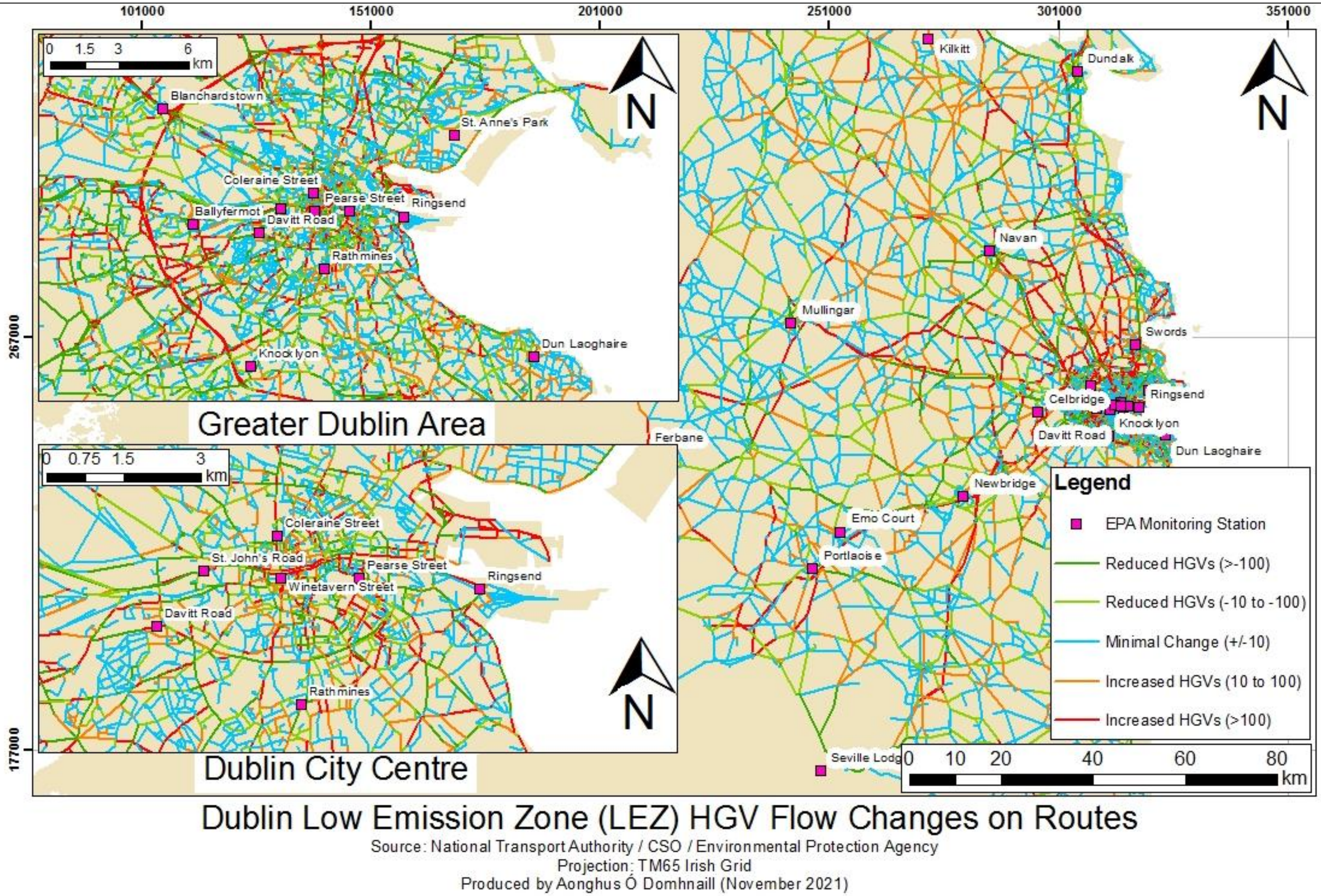


Figure 6.27: Dublin LEZ Scenario HGV Flow Changes on Routes

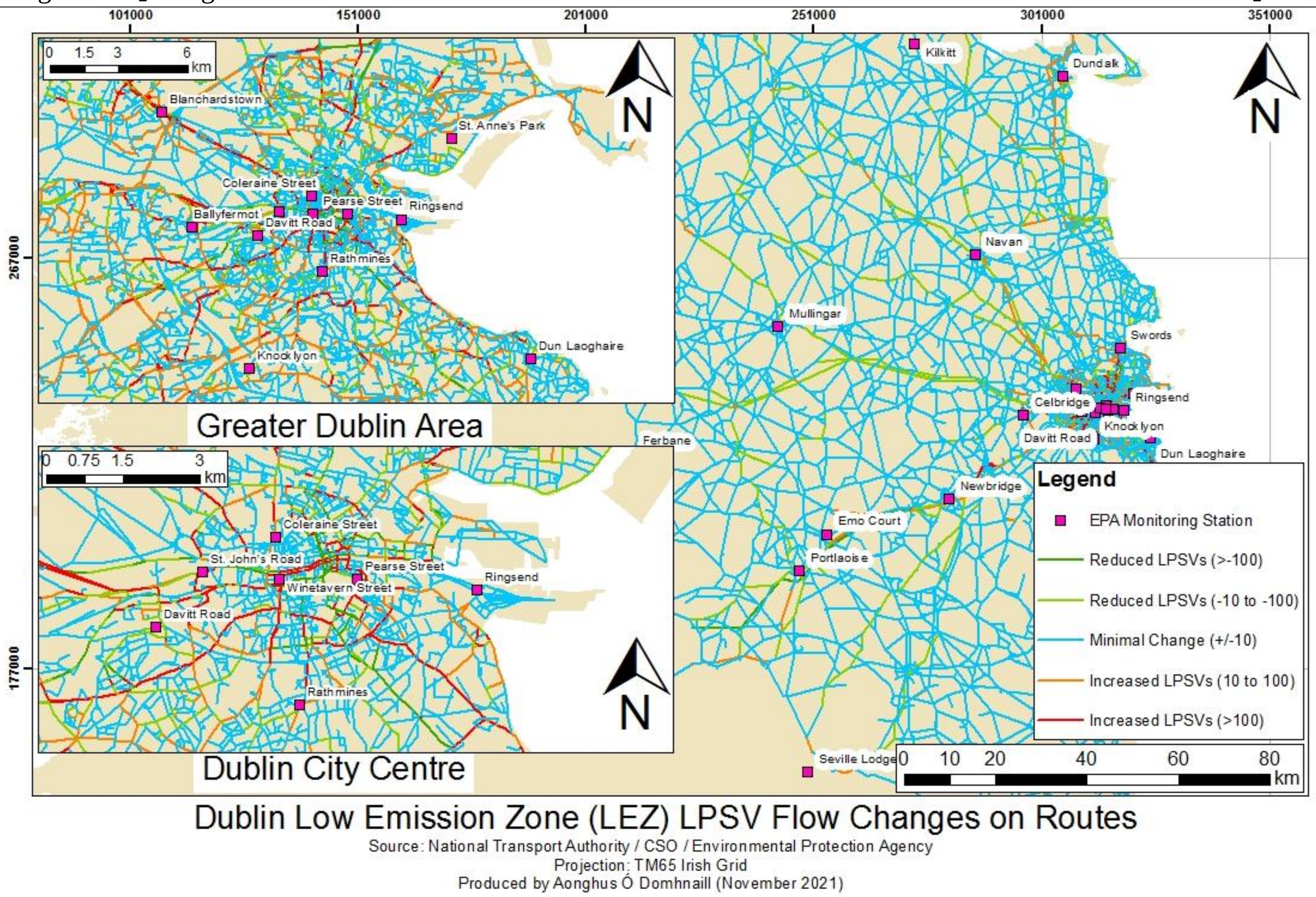


Figure 6.28: Dublin LEZ Scenario LPSV Flow Changes on Routes

Table 6.34 shows the resulting IDWVKT values for all directional sectors at all modelled locations for the 2019 modelled scenario as well as the 2030 LEZ scenario. The IDWVKT reduced in the majority of directional sectors for all modelled locations within Dublin. It would be expected that due to the comparison between 2019 and a future year (2030) that the IDWVKT statistics would increase in this time period, therefore, these results highlight that the LEZ has the potential to negate this increase and even reduce the overall IDWVKT in a number of instances in comparison to the 2019 statistics. As expected, the IDWVKT statistics were largely unchanged for the modelled locations outside of Dublin and this could be due to a number of reasons such as the trips in these locations are not affected by the LEZ as the origin / destination of the trips are not in Dublin city centre or the transport options in these areas for travel to the Dublin city centre region are limited and therefore transport choice is largely unchanged. In some cases, the AADT flows on routes reduced by >10%, mainly due to reductions in car flows. Accounting for vehicle fleet emissions within the enhanced WS-LUR model identified that these reductions were offset by increases in heavier emitting vehicles (e.g. HGVs or LGVs) despite the increase in HGV / LGV numbers being less than the decrease in car numbers. In this scenario, the benefit of the enhanced WS-LUR model is presented as the original model would have overestimated the influence of the car reductions and underestimated the influence of the increase in HGVs and LGVs due to all vehicles being considered equal.

The most noticeable increases in IDWVKT were the west directional sector at the Davitt Road station, the southwest directional sector for the Dun Laoghaire monitoring station and the south directional sector at the St. John’s Road station, as shown in Table 6.34. The west directional sector at the Davitt Road monitoring station experienced an increase of ~ 350 000 km, which was due to an increase in flows for cars/ taxis, LCVs and HDVs, as shown in Figure 6.25, Figure 6.26 and Figure 6.27. A number of factors could influence this change such as the Davitt Road station being located just outside of the LEZ zone, meaning that traffic from the west would only be impacted by the LEZ charge if it planned to travel further east past this monitoring station and into the city. The route to the west of the Davitt Road monitoring station is the main route from the N7 / M7 towards the city centre, the R810, which would be the most direct route for HGV traffic towards Dublin Port. Trips to Dublin Port may be less likely to be influenced by the LEZ charge.

The southwest directional sector at the Dun Laoghaire monitoring station experienced an increase of ~ 40 000 km (see Table 6.34). This station is located more than 7 km outside of the LEZ and therefore traffic is not affected by the charge unless they are travelling towards the city centre. The traffic flows for cars/taxis and LGVs increased considerably on a number of routes to the southwest and could be mainly due to the increase in the number of vehicles from 2019 to 2030, which are expected to increase by approximately 22% in this period, as shown in Table 6.33. The south directional sector at the St. John's Road station experienced an increase of ~ 150 000 km. A number of factors could contribute to this increase such as the traffic travelling to essential services such as health services (St. James' Hospital) which are trips that will be required irrespective of the introduction of an LEZ charge. The other factor is the largely residential area further south, where a significant number of cars and LGVs trips would be originating from within the LEZ. These vehicles were exempt from the LEZ charge within the modelling completed by the National Transport Authority and therefore the vehicle kilometres travelled within this area would be largely unchanged.

The city centre modelled locations (Coleraine Street, Pearse Street, Ringsend, St. John's Road and Winetavern Street) located within the LEZ experienced decreases in the majority of directional sectors highlighting the effectiveness of the LEZ charge in deterring vehicles from entering the zone. Flows for 2030 would be expected to be greater than 2019 flows in a direct comparison of a Do-Minimum scenario, as described in Section 6.4.1.1, but the LEZ had a significant impact which resulted in 2030 flows for both cars and LGVs being less than 2019 flows. The directional sectors at these modelled locations that experienced increases in IDWVKT were mainly affected by the increase in HGV traffic from 2019 to 2030 that would continue to use routes through the city centre to get to Dublin Port despite the LEZ. As previously stated above, in the case that the percentage increase in vehicle flows between the pre- and post-mitigation measure scenarios is less than the 2019 - 2030 growth rates, shown in Table 6.33, the implementation of an LEZ in the Greater Dublin Area will be seen to have a positive impact at these locations. This was the case for all the directional sectors that experienced increases at the city centre modelled locations.

Table 6.34: Inverse Distance Weighted Vehicle Kilometres Travelled by Directional Sector for Dublin LEZ Scenario

		INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED							
EPA Monitoring Station	**Scenario**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot, Dublin	Pre-Mitigation Measure	194 768	161 553	188 732	145 847	263 197	216 931	416 008	306 598
	Post-Mitigation Measure	172 870	132 928	158 317	142 956	251 744	202 710	340 578	240 888
Blanchardstown, Dublin	Pre-Mitigation Measure	77 790	236 696	439 530	345 875	396 828	208 504	97 705	482 825
	Post-Mitigation Measure	85 638	222 967	452 939	198 148	345 531	195 052	92 696	341 205
Celbridge, Kildare	Pre-Mitigation Measure	117 837	87 257	171 818	29 621	12 755	5 107	30 940	33 278
	Post-Mitigation Measure	116 459	87 426	56 993	165 098	26 029	5 637	36 386	32 787
Coleraine Street, Dublin	Pre-Mitigation Measure	162 434	240 294	208 940	260 007	275 536	277 578	173 414	121 639
	Post-Mitigation Measure	176 212	218 456	186 354	228 198	224 458	266 484	101 211	108 470
Davitt Road, Dublin	Pre-Mitigation Measure	171 050	253 387	252 913	126 347	126 989	301 517	394 107	155 163
	Post-Mitigation Measure	140 271	210 879	244 713	115 794	107 790	288 443	744 653	129 950
Dún Laoghaire, Dublin	Pre-Mitigation Measure	16 682	5 914	8 623	9 422	116 102	174 304	116 111	60 485
	Post-Mitigation Measure	18 572	4 307	9 285	9 026	107 161	215 231	105 612	58 833
Emo Court, Laois	Pre-Mitigation Measure	9 575	2 423	6 579	11 143	57 071	14 051	8 181	175
	Post-Mitigation Measure	10 057	2 247	5 893	11 102	58 572	13 881	8 176	170
Kilkitt, Monaghan	Pre-Mitigation Measure	3 127	865	737	846	1 416	2 607	239	3 265
	Post-Mitigation Measure	2 860	737	533	911	1 529	2 016	218	2 517
Knocklyon, Dublin	Pre-Mitigation Measure	137 876	123 269	102 029	169 817	74 153	169 440	217 199	329 821
	Post-Mitigation Measure	119 013	117 770	120 818	144 800	61 573	145 985	197 569	308 774

INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED

EPA Monitoring Station	Scenario	N	NE	E	SE	S	SW	W	NW
Navan, Meath	Pre-Mitigation Measure	21 784	79 470	80 166	51 128	55 467	26 890	28 630	53 425
	Post-Mitigation Measure	16 006	84 807	69 613	53 080	55 296	25 127	24 232	48 994
Newbridge, Kildare	Pre-Mitigation Measure	33 724	69 436	32 052	329 566	6 763	26 971	29 994	26 801
	Post-Mitigation Measure	31 189	82 073	32 178	351 851	6 416	25 457	27 885	26 771
Pearse Street, Dublin	Pre-Mitigation Measure	285 306	217 652	124 010	160 562	212 096	203 181	267 116	314 616
	Post-Mitigation Measure	268 335	212 754	133 493	115 657	199 564	161 574	224 135	292 428
Portlaoise, Laois	Pre-Mitigation Measure	4 717	152 320	23 860	121 565	19 703	38 123	49 847	19 311
	Post-Mitigation Measure	5 583	154 973	24 059	126 938	19 749	38 955	49 862	18 844
Rathmines, Dublin	Pre-Mitigation Measure	285 126	194 927	155 137	136 245	114 889	143 960	132 718	174 800
	Post-Mitigation Measure	227 936	161 999	119 421	126 060	122 711	136 047	116 149	152 197
Ringsend, Dublin	Pre-Mitigation Measure	115 356	18 791	11 825	19 563	163 191	167 176	255 054	232 397
	Post-Mitigation Measure	133 963	31 158	18 649	14 745	104 779	130 356	228 948	215 216
Seville Lodge, Kilkenny	Pre-Mitigation Measure	334	3 004	4	0*	0*	0*	0*	0*
	Post-Mitigation Measure	213	1 937	6	0*	0*	0*	0*	0*
St Anne’s Park, Dublin	Pre-Mitigation Measure	111 881	65 595	15 942	7 134	11 205	91 542	169 472	140 068
	Post-Mitigation Measure	97 122	66 878	15 237	6 739	12 239	97 366	166 064	135 973
St. John’s Road, Dublin	Pre-Mitigation Measure	140 106	398 692	372 956	185 819	155 607	164 858	421 177	102 699
	Post-Mitigation Measure	128 356	168 646	312 784	160 028	309 622	153 051	219 681	78 560
Swords, Dublin	Pre-Mitigation Measure	11 444	120 126	55 381	286 570	259 513	52 740	22 701	54 117
	Post-Mitigation Measure	20 836	137 815	72 894	290 794	233 665	70 512	37 505	64 175

INVERSE DISTANCE WEIGHTED VEHICLE KILOMETRES TRAVELLED

EPA Monitoring Station	Scenario	N	NE	E	SE	S	SW	W	NW
Winetavern Street, Dublin	Pre-Mitigation Measure	221 971	334 984	207 967	242 724	237 848	196 574	261 188	219 727
	Post-Mitigation Measure	211 418	289 338	207 108	179 588	192 507	163 608	214 169	180 609

* No traffic flow data within directional sector

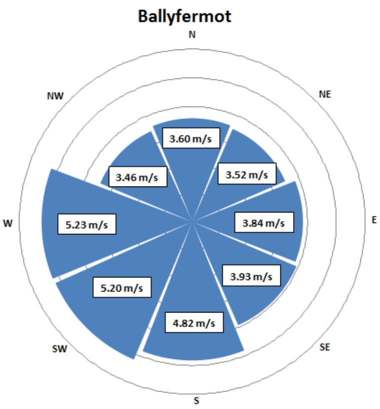
6.4.1.2. Meteorological, Road Density, Commercial Properties and Land Use Data

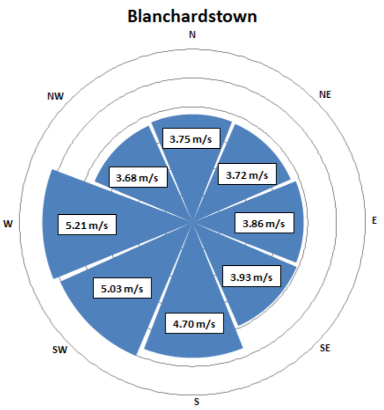
This section introduces the sources of data for the variables which were unaffected by the mitigation measure (meteorological, road density, commercial properties and land use) and therefore values were constant for both the pre- and post-mitigation measure scenarios. The methodology used to analyse the data was the same as that used to develop the background data for the WS-LUR model described in Chapter 3.

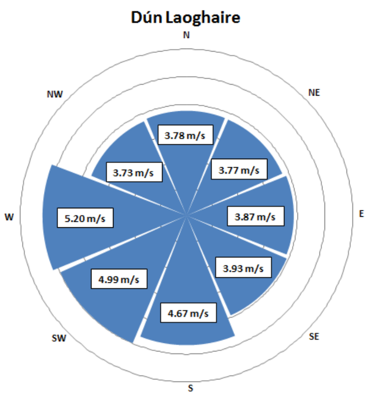
The meteorological data used in this analysis was obtained from the Met Éireann historical database and included data for all monitoring stations including offshore stations (Met Éireann, 2020). The same data that was used for the pre-COVID scenario in the COVID analysis was used to analyse the mitigation measure impacts and represented 2019 conditions, as described in Section 5.2.3. The methodology used to analyse the data was the same as that used for the meteorological data in the WS-LUR model development, described in Section 3.3.1. Table 6.35 and Figure 6.29 present the statistics and wind roses for the wind speeds by wind directional sectors for the pre- and post-mitigation scenarios at all modelled locations whilst Table 6.36 and Figure 6.30 present the statistics and wind roses for the wind direction proportions.

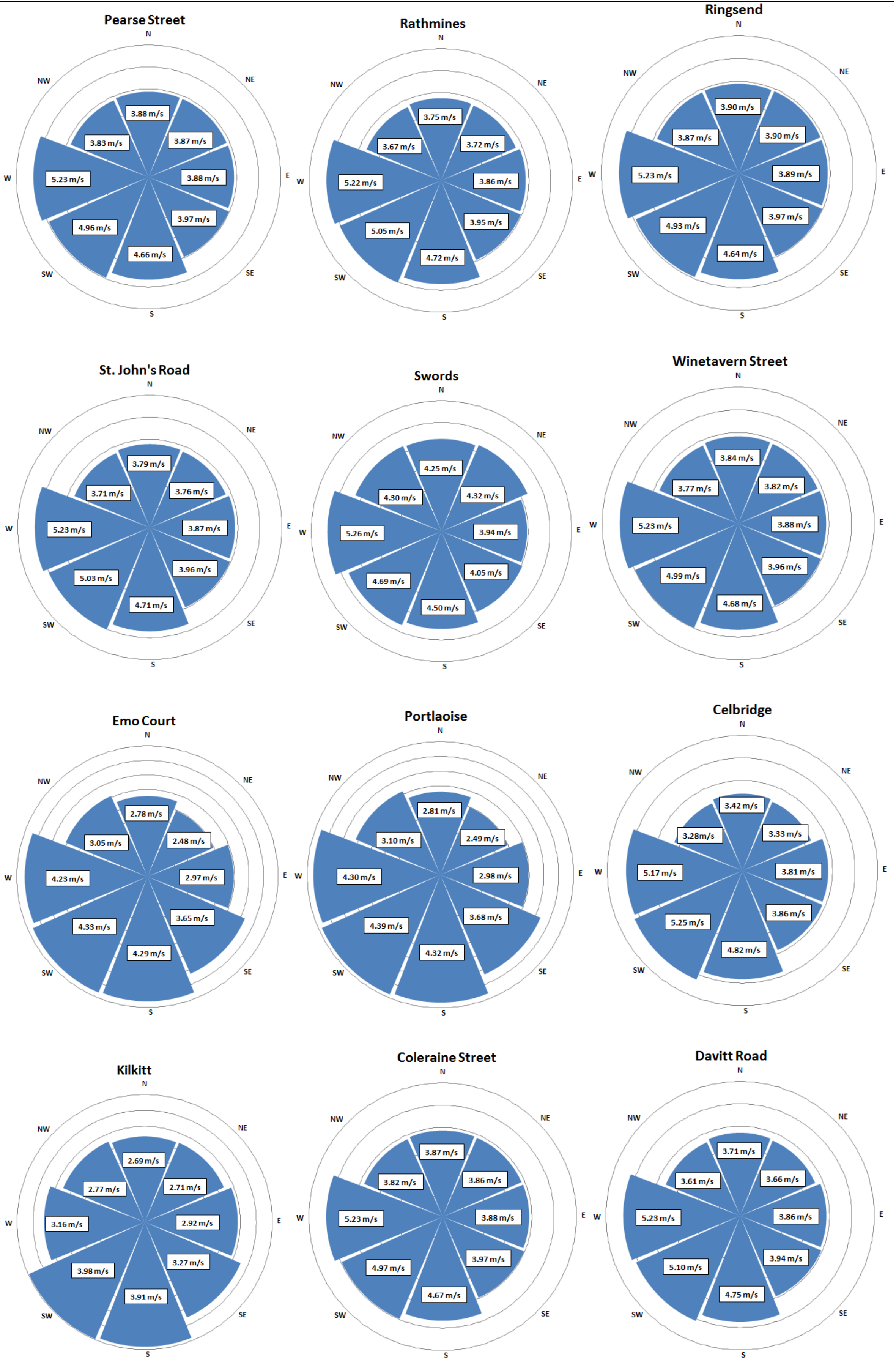
Table 6.35: Wind Speed by Directional Sector for Pre- and Post-Mitigation Measure Scenarios

WIND SPEED (m/s)								
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	3.60	3.52	3.84	3.93	4.82	5.20	5.23	3.46
Blanchardstown	3.75	3.72	3.86	3.93	4.70	5.03	5.21	3.68
Celbridge	3.42	3.33	3.81	3.86	4.82	5.25	5.17	3.28
Coleraine Street	3.87	3.86	3.88	3.97	4.67	4.97	5.23	3.82
Davitt Road	3.71	3.66	3.86	3.94	4.75	5.10	5.23	3.61
Dún Laoghaire	3.78	3.77	3.87	3.93	4.67	4.99	5.20	3.73
Emo Court	2.78	2.48	2.97	3.65	4.29	4.33	4.23	3.05
Kilkitt	2.69	2.71	2.92	3.27	3.91	3.98	3.16	2.77
Knocklyon	3.57	3.48	3.83	3.92	4.84	5.22	5.23	3.41
Navan	3.37	3.42	3.83	3.65	4.39	4.83	4.88	3.48
Newbridge	3.02	2.68	3.38	3.51	4.68	5.16	4.91	2.99
Pearse Street	3.88	3.87	3.88	3.97	4.66	4.96	5.23	3.83
Portlaoise	2.81	2.49	2.98	3.68	4.32	4.39	4.30	3.10
Rathmines	3.75	3.72	3.86	3.95	4.72	5.05	5.22	3.67
Ringsend	3.90	3.90	3.89	3.97	4.64	4.93	5.23	3.87
Seville Lodge	3.17	2.73	2.95	3.96	4.65	4.81	4.71	3.51
St. Anne's Park	4.05	4.08	3.91	4.01	4.58	4.83	5.24	4.05
St. John's Road	3.79	3.76	3.87	3.96	4.71	5.03	5.23	3.71
Swords	4.25	4.32	3.94	4.05	4.50	4.69	5.26	4.30
Winetavern Street	3.84	3.82	3.88	3.96	4.68	4.99	5.23	3.77





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St. John's Road
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Swords
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Winetavern Street
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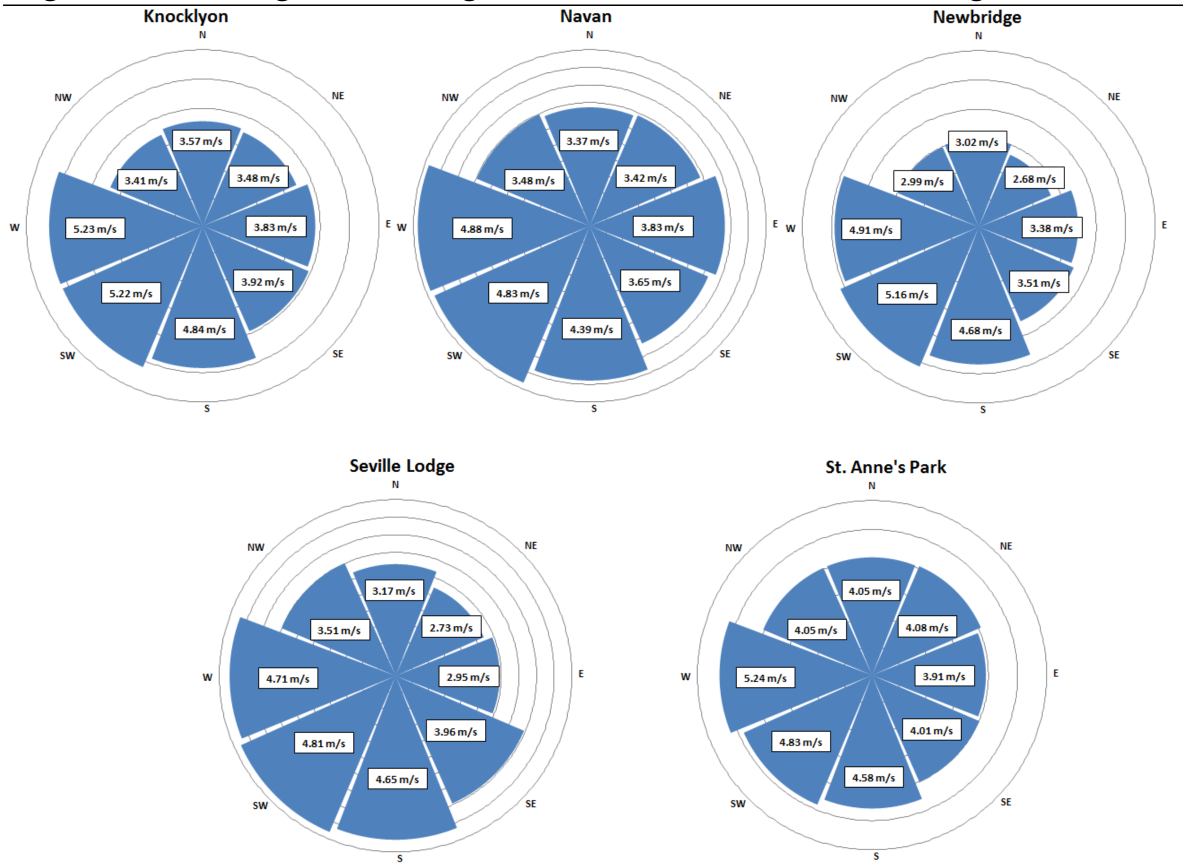
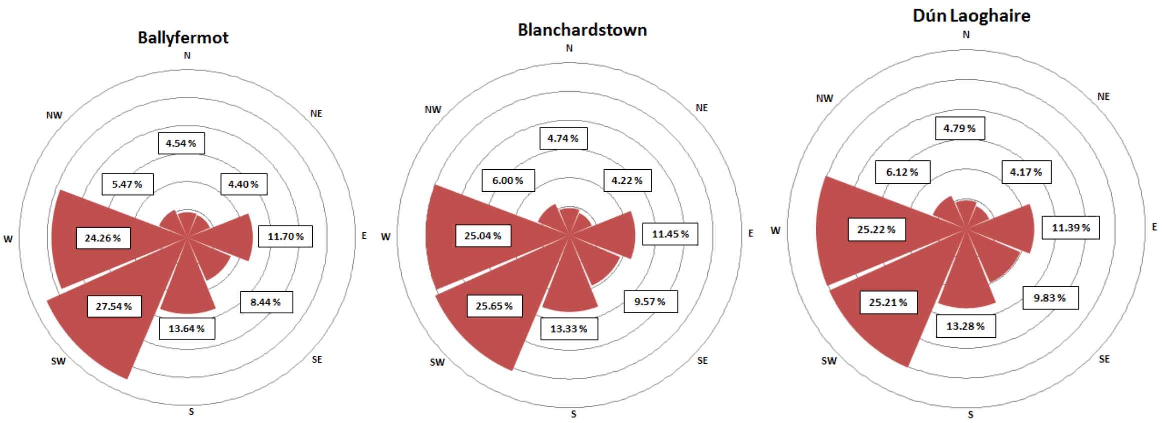


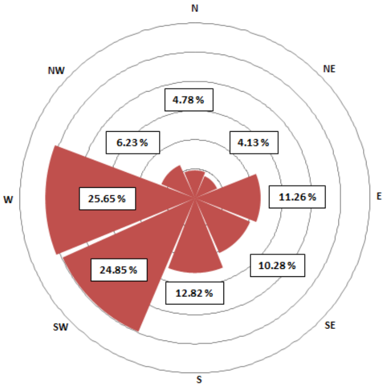
Figure 6.29: Wind Speed Roses for Pre- and Post-Mitigation Scenarios

Table 6.36: Wind Direction Proportions by Directional Sector for Pre- and Post-Mitigation Measure Scenarios

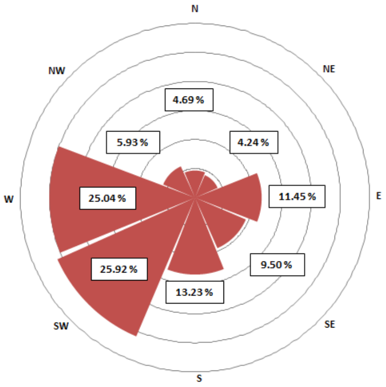
	WIND PROPORTION (%)							
EPA Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Ballyfermot	4.54	4.40	11.70	8.44	13.64	27.54	24.26	5.47
Blanchardstown	4.74	4.22	11.45	9.57	13.33	25.65	25.04	6.00
Celbridge	4.58	4.48	11.95	7.61	14.57	28.09	23.44	5.29
Coleraine Street	4.77	4.13	11.27	10.25	12.81	24.93	25.63	6.21
Davitt Road	4.65	4.28	11.52	9.20	13.33	26.40	24.82	5.79
Dún Laoghaire	4.79	4.17	11.39	9.83	13.28	25.21	25.22	6.12
Emo Court	7.88	3.54	6.68	14.59	22.71	16.15	18.37	10.08
Kilkitt	5.61	3.73	12.34	10.94	16.36	21.85	19.96	9.21
Knocklyon	4.52	4.43	11.76	8.23	13.78	27.79	24.09	5.40
Navan	5.35	4.11	11.85	8.90	16..31	23.42	23.61	6.46
Newbridge	6.43	3.81	9.97	9.83	19.67	22.16	20.94	7.18
Pearse Street	4.78	4.13	11.26	10.28	12.82	24.85	25.65	6.23
Portlaoise	7.91	3.56	6.46	14.84	22.88	15.99	18.38	9.98
Rathmines	4.69	4.24	11.45	9.50	13.23	25.92	25.04	5.93
Ringsend	4.81	4.10	11.21	10.48	12.74	24.54	25.79	6.32
Seville Lodge	8.75	3.90	5.34	13.97	21.82	17.02	18.62	10.58
St. Anne's Park	4.90	3.97	10.98	11.40	12.21	23.35	26.53	6.66
St. John's Road	4.71	4.21	11.40	9.73	13.08	25.65	25.22	6.01
Swords	5.00	3.81	10.67	12.61	11.47	21.82	27.51	7.10
Winetavern Street	4.75	4.17	11.32	10.02	12.94	25.23	25.45	6.13



Pearse Street



Rathmines



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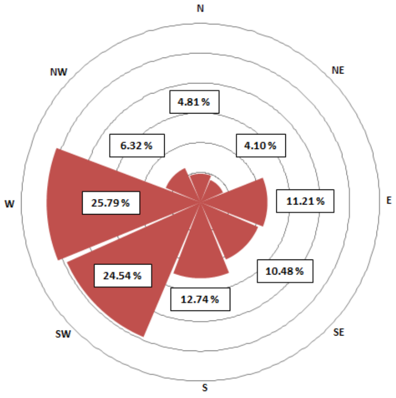
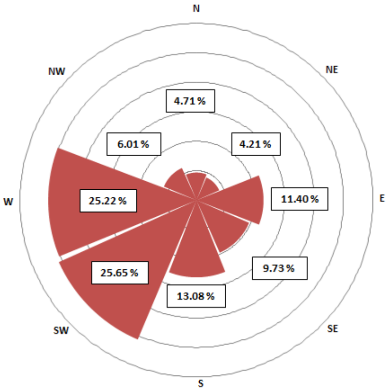
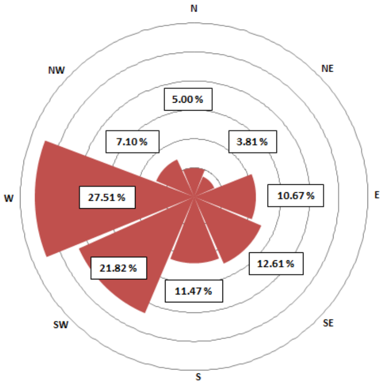


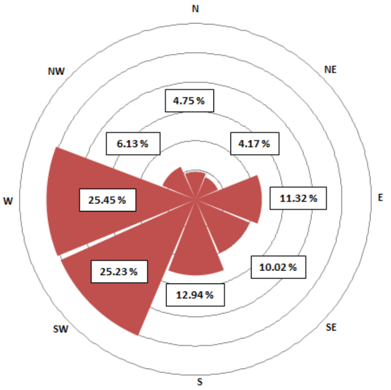
St. John's Road



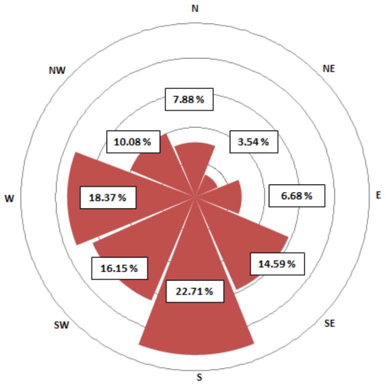
Swords



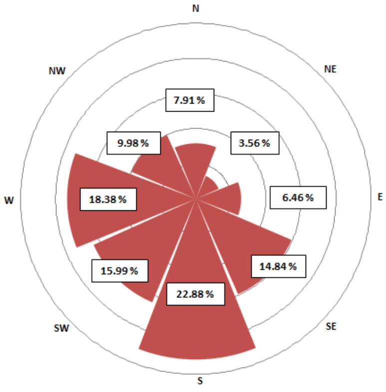
Winetavern Street



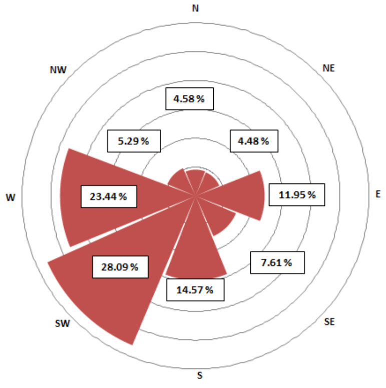
Emo Court



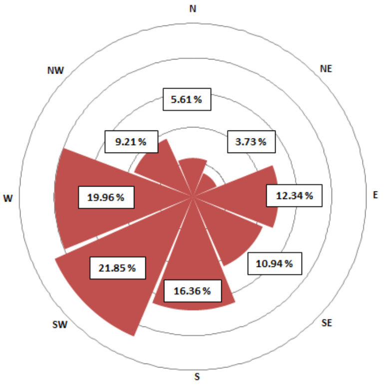
Portlaoise



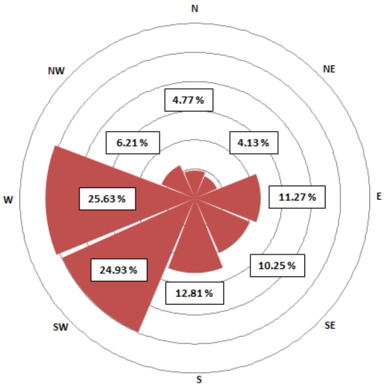
Celbridge



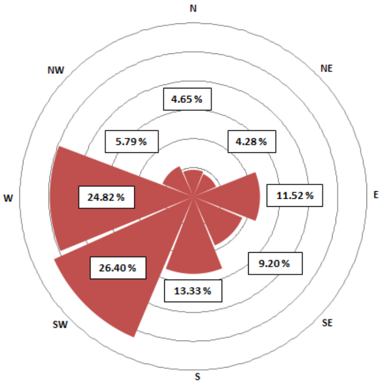
Kilkitt



Coleraine Street



Davitt Road



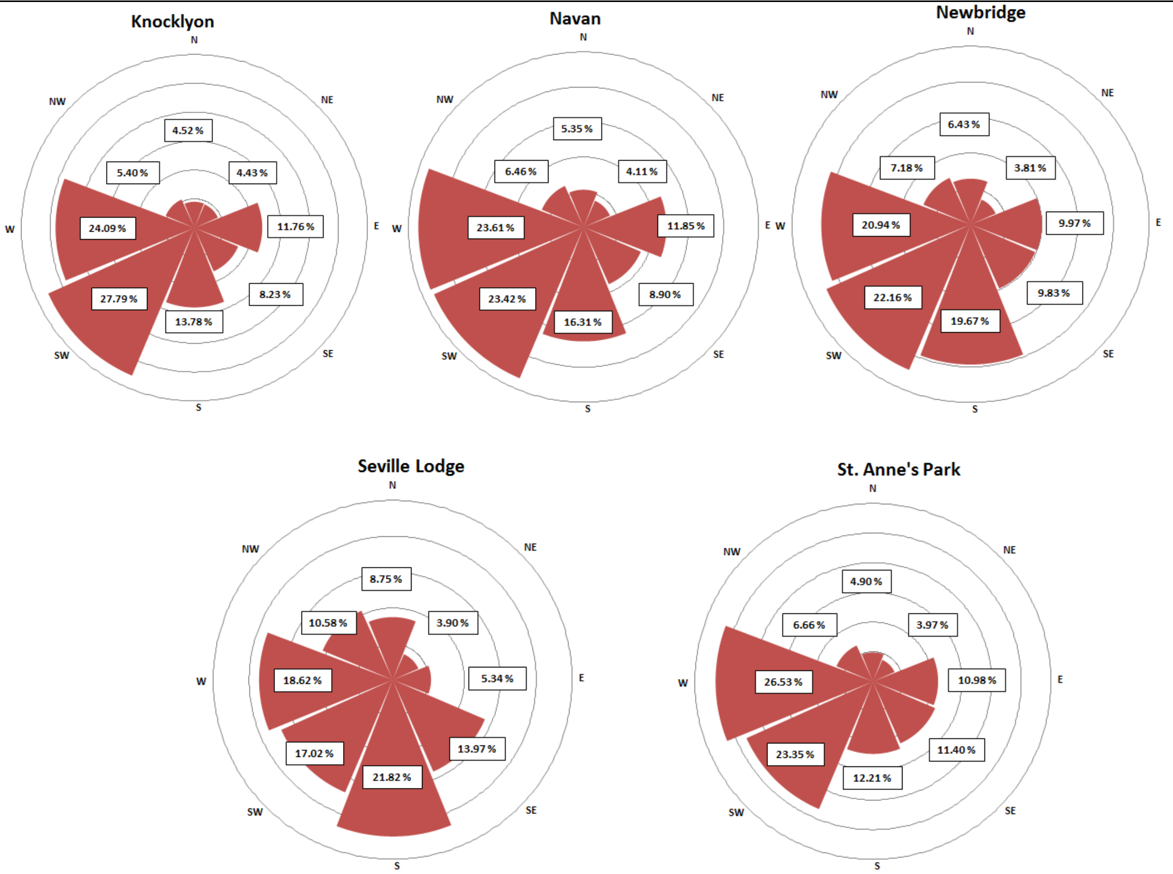


Figure 6.30: Wind Direction Proportion Roses for Pre- and Post-Mitigation Scenarios

The road density data used for this analysis was obtained from the National Transport Authority's model for the east region of Ireland (National Transport Authority, 2020). This contained information in relation to all links located in the province of Leinster and was the same output used for the analysis of the performance of the ambient NO_2 concentration model during the 2016 to 2018 period, as described in Sections 5.2.1 and 5.2.5. The methodology used to analyse the data was the same as that used for the road density data in the WS-LUR model development, described in Section 3.3.4.

The commercial properties data was sourced from An Post / Geodirectory and represented 2019 conditions (GeoDirectory, 2020). This mitigation measure focused on the vehicle kilometres travelled therefore the commercial properties were unchanged for the pre- and post-mitigation measure scenarios. The data for the pre-mitigation measure scenario was the same as that used for the pre-COVID scenario, described in Section 5.2.2. The methodology used to analyse the data was the same as that used for the commercial properties data in the WS-LUR model development, described in Section 3.3.3.

The land use data was sourced from the European Environment Agency / Copernicus database (European Environment Agency & Copernicus, 2020) and was the same data used to represent the 2018 conditions in the COVID analysis, as described in Section 5.2.5. The methodology used to analyse the data was the same as that used for the land use data in the WS-LUR model development, described in Section 3.3.2.

6.4.1.3. Methodology and Data Summary

The statistics generated as part of the data analyses described between Sections 6.3.1.1 and 6.3.1.3 for the Dublin Low Emission Zone scenario were collated and input into the WS-LUR model. The manual entry approach was selected within the model and the statistics for each of the predictor variables were input into the respective sections (Section A for meteorological data; Section B for land use data; Section C for commercial properties data and Section D for traffic data (IDWVKT and road density)). The modelled concentrations for the post-mitigation measure scenario were generated for all modelled locations and compared with modelled concentrations for the pre-mitigation measure scenario (2019 conditions), which were calculated previously in the COVID analysis described in Sections 5.2 and 5.3. Results of the concentration changes / comparison are provided in the following section.

6.4.2. Results

The results of the data analysis described within Section 6.4.1 were collated and input into the WS-LUR model to determine the modelled ambient NO_2 concentrations at each of the modelled locations for both the pre- and post-mitigation measure scenarios. The results presented in Table 6.37 and Figure 6.31 show the concentration changes at EPA monitoring station locations due to the introduction of an LEZ in the Dublin City Centre region. All of the city centre monitoring station locations; Coleraine Street, Pearse Street, Ringsend, St. John's Road and Winetavern Street experienced significant decreases in ambient NO_2 concentrations of 1.9, 1.6, 1.2, 3.0 and 2.1 $\mu g / m^3$ respectively, which equate to reductions of 4.76%, 4.21%, 5.61%, 8.8% and 4.77% respectively at these stations. These reductions were mainly due to the substantial IDWVKT decreases presented in Section 6.4.1.1 occurring in the predominant wind direction sectors.

Mixed results were achieved at the Dublin modelled locations outside of the LEZ with the Davitt Road and Dun Laoghaire stations increasing by 4.0 and 0.4 μg / m^3 respectively due to the factors described in Section 6.4.1.1. In the case of the Davitt Road station, it was located on the boundary of the LEZ and the main increases in IDWVKT were to the west, which was both outside of the zone and in one of the predominant wind directions. In the case of the Dun Laoghaire station, it was located more than 7 km outside of the zone and increases in IDWVKT were experienced in the southwest sector, which was one of the predominant wind direction sectors. Multiple routes surrounding the Swords monitoring station experienced increased flows for all vehicle types suggesting that the traffic growth rate is greater than the effect of the LEZ at this location, leading to the modelled concentration increase of 0.5 μg / m^3. The ambient NO_2 concentration at St.Anne's Park was largely unchanged, highlighting that the LEZ effect negated the increased flows that would be experienced from 2019 to 2030. The remaining 4 modelled locations in Dublin (Ballyfermot, Blanchardstown, Knocklyon and Rathmines) experienced reductions in the range of 0.8 to 1.8 μg / m^3, equivalent to reductions of 2.95 to 5.37% in ambient NO_2 at these sites.

Table 6.37: Dublin LEZ Impacts on Ambient NO_2 Concentrations

Monitoring Station	Modelled Scenario	Modelled Concentration (μg / m^3)	Difference (μg / m^3)
Ballyfermot, Dublin	Pre-Mitigation Measure	33.5	-1.8
	Post-Mitigation Measure	31.7	
Blanchardstown, Dublin	Pre-Mitigation Measure	39.8	-1.8
	Post-Mitigation Measure	38.0	
Celbridge, Kildare	Pre-Mitigation Measure	13.6	0.0
	Post-Mitigation Measure	13.6	
Coleraine Street, Dublin	Pre-Mitigation Measure	39.9	-1.9
	Post-Mitigation Measure	38.0	
Davitt Road, Dublin	Pre-Mitigation Measure	34.8	4.1
	Post-Mitigation Measure	38.9	
Dún Laoghaire, Dublin	Pre-Mitigation Measure	22.7	0.4
	Post-Mitigation Measure	23.1	
Emo Court, Laois	Pre-Mitigation Measure	9.0	0.0
	Post-Mitigation Measure	9.0	
Kilkitt, Monaghan	Pre-Mitigation Measure	4.8	0.0
	Post-Mitigation Measure	4.8	
Knocklyon, Dublin	Pre-Mitigation Measure	21.3	-0.8
	Post-Mitigation Measure	20.5	
Navan, Meath	Pre-Mitigation Measure	17.2	-0.2
	Post-Mitigation Measure	17.0	
Newbridge, Kildare	Pre-Mitigation Measure	12.1	0.1
	Post-Mitigation Measure	12.2	
Pearse Street, Dublin	Pre-Mitigation Measure	38.0	-1.6
	Post-Mitigation Measure	36.4	
Portlaoise, Laois	Pre-Mitigation Measure	15.8	0.1
	Post-Mitigation Measure	15.8	
Rathmines, Dublin	Pre-Mitigation Measure	30.5	-0.9
	Post-Mitigation Measure	29.7	
Ringsend, Dublin	Pre-Mitigation Measure	21.4	-1.2
	Post-Mitigation Measure	20.1	
Seville Lodge, Kilkenny	Pre-Mitigation Measure	4.6	0.0
	Post-Mitigation Measure	4.6	
St Anne’s Park, Dublin	Pre-Mitigation Measure	14.8	0.0
	Post-Mitigation Measure	14.7	
St. John’s Road, Dublin	Pre-Mitigation Measure	34.1	-3.0
	Post-Mitigation Measure	31.1	

Monitoring Station	Modelled Scenario	Modelled Concentration ($\mu g / m^3$)	Difference ($\mu g / m^3$)
Swords, Dublin	Pre-Mitigation Measure	21.8	0.5
	Post-Mitigation Measure	22.3	
Winetavern Street, Dublin	Pre-Mitigation Measure	44.0	-2.1
	Post-Mitigation Measure	41.9	

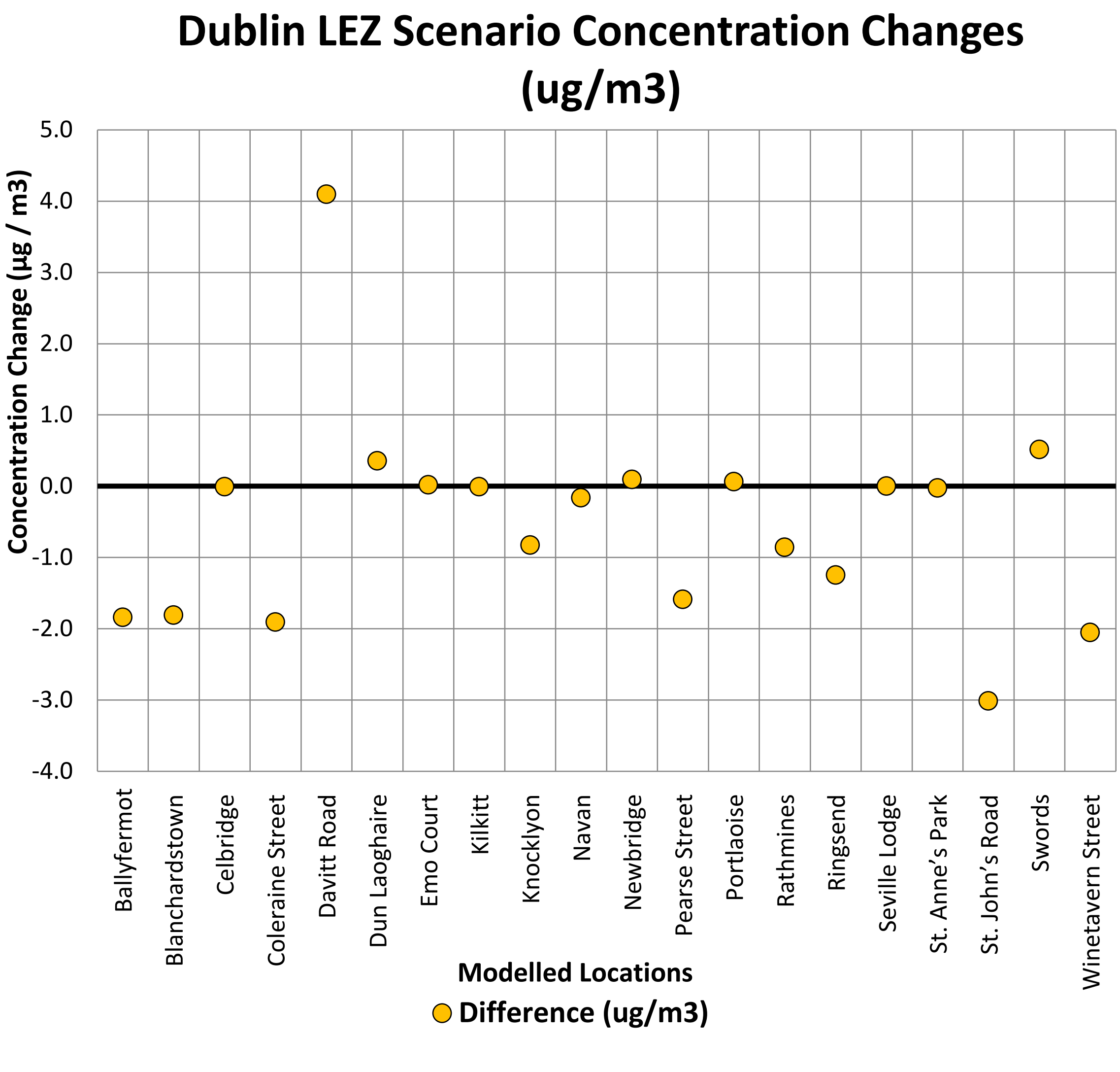


Figure 6.31: Dublin LEZ Concentration Change at Modelled Locations

6.4.3. Conclusions

This analysis evaluated the effects of an LEZ within the Dublin City Centre area, by determining the changes in NO_2 concentrations due to the changes in traffic flows in response to the implementation of the LEZ. The comparison was between 2019 conditions and a future year (2030), therefore the expected increases in vehicle numbers due to growth rates for future year predictions were considered in the comparison to determine the effects of the LEZ. The results of this mitigation measure, approximately 5% reductions in NO_2 concentrations, align with results achieved by LEZs in other European countries (Muller & Le Petit, 2019).

A number of positive impacts were expected throughout the Leinster province and were confirmed in this analysis. These include:

- Significant reductions in flows for private vehicle types such as cars were experienced both inside and outside of the LEZ.
- The LEZ significantly improved air quality at modelled locations within the LEZ with NO_2 reductions of 1.6 to 3.0 μg/m^3 at Dublin City Centre modelled locations (St. John's Road, Winetavern Street, Pearse, Street and Coleraine Street). From 2019 to 2030, vehicle numbers are expected to increase significantly but the LEZ was able to negate those effects and further reduce flows for cars on the majority of routes within the city. The LEZ also significantly reduced HGVs on the majority of routes within the city apart from the main corridors linking the city centre/Dublin Port to the national routes out of Dublin.
- The majority of modelled locations bordering the LEZ also experienced significant concentration reductions between 0.8 and 1.8 μg/m^3. There were less cars travelling into the area covered by the LEZ and these modelled locations were located further away from the main corridors into the city, therefore HGVs were also reduced considerably.

6.5. Conclusion

The research presented in this chapter identified the successful integrated application of transportation, emissions and LUR modelling to assess the performance of various mitigation measures. The effects of a number of mitigation measures which include the relocation of a business hub, the removal of diesel vehicles from the public service vehicle fleet, the construction of a ring road around a city and the introduction of an LEZ within a city were assessed by comparing pre- and post-mitigation measure scenarios and the determining the resultant changes in concentrations.

The mitigation measures had a significant effect on pollutant concentrations within Dublin City Centre with reductions in the range of 1.6 μg/m^3 and 3.0 μg/m^3 experienced in the LEZ mitigation scenario, reductions between 1.0 μg/m^3 and 1.8 μg/m^3 in the removal of diesel from the public service vehicle fleet mitigation scenario and reductions between 0.5 μg/m^3 and 1.9 μg/m^3 from the Blanchardstown business hub relocation. These results are significant as they have the potential to considerably reduce concentrations in locations which are currently experiencing high levels of pollution.

Outside of the Dublin City Centre region, the concentrations reductions were smaller but still produced positive improvements in air quality throughout the areas of the Ulster and Leinster provinces covered by the East Region of the NTA model. The LEZ mitigation measure resulted in reductions between 0.8 μg/m^3 and 1.8 μg/m^3. The relocation of the Blanchardstown business hub produced significant reductions in the range of 0.3 μg/m^3 and 1.7 μg/m^3. The removal of diesel vehicles from the public service vehicle fleet focused on areas within the Greater Dublin Area where the public service vehicles mainly operate and achieved reductions in the range of 0.3 μg/m^3 and 0.9 μg/m^3.

The ring road mitigation measure produced varying results, with increases in the range of 1.8 μg/m^3 and 3.6 μg/m^3 modelled at the intersections between the existing major routes into Cork City and the new ring road, which would be expected due to the increase in traffic at these locations. These locations were experiencing low levels of pollution in the pre-mitigation scenario and did not exceed the 10 μg/m^3 limit in the post-mitigation scenario. Smaller increases (in the range of 0.1 μg/m^3 and 0.2 μg/m^3) were modelled in the north and west of the city, areas which were in close proximity to the ring road and the ring road was located on the pre-dominant wind direction side of these locations. Significant reductions in the range of 0.4 μg/m^3 and 1.3 μg/m^3 were modelled in areas to the south and east of the city, near the existing major route around the city, which were the most heavily polluted locations considered in this analysis in the pre-mitigation scenario.

7. Discussion

The main objective of this thesis was to develop a WS-LUR model which has the capability of identifying the meteorological, environmental and traffic conditions which contribute to high levels of NO_2 and the model could also be utilised to assess the impacts of mitigation measures. The results of the research presented in this thesis are discussed in greater detail within this chapter. The results of each section of this research are combined within this discussion chapter to determine the suitability of this model to accurately estimate NO_2 concentrations at various locations throughout Ireland, estimate the performance of mitigation measures and therefore the use of the model for future policy recommendations. The main contributions of this research to the LUR modelling study field are identified as well as the limitations of the research. Areas of future research which extend from this work are also considered within this chapter.

7.1. Main Contributions and Findings

The research described in Chapter 3 presented a new method of including details of the vehicle fleet breakdown within the traffic variable of a WS-LUR model. This approach is of use for LUR models which have determined that AADT flows or flows by a particular vehicle type are linked to NO_2 concentrations but do not account for all vehicle types. This retains the link to the original model and ensures that the model can account for every vehicle type flow when estimating pollutant concentrations. This has a number of benefits when estimating NO_2 concentrations at a study location, including:

- A better representation of the traffic flows surrounding a study location as it segregates the AADT flow into a flow for each vehicle type and weights each of the vehicle types based on their emission rates relative to the average vehicle in the fleet.
- Accounting for the varying fleets on each of the routes surrounding a study location as the vehicle fleet breakdown can vary significantly from one route to another. This would improve the model when analysing a study location and the surrounding routes have significant differences in vehicle fleet breakdown. An example of this would be major haulage routes which can have an above average

proportion of HGVs in comparison to other routes and these vehicles typically emit significantly more NO_2 than the average vehicle. Therefore, in the case that the total flow on a haulage route and a standard route were equal, the enhanced WS-LUR model has the capability of distinguishing between these routes using the weightings for vehicle types and therefore the resultant IDWVKT would be greater on the haulage route due to the heavier emitting HGVs. Similarly, city centre routes typically have greater numbers of SPSVs and LPSVs (mainly diesel fuelled vehicles that emit greater levels of NO_2 in comparison to an average vehicle) in comparison to the minor suburban / residential routes. Hence, if a city centre route and suburban route had the same AADT flow, the route with greater numbers of SPSVs and LPSVs would have a larger IDWVKT value. The update to the enhanced WS-LUR model would apply a heavier weighting to these vehicle types as they are predominantly diesel powered which emits more NO_2 than other fuel types. Therefore, the larger IDWVKT value would result in higher NO_2 concentration estimates at a study location.

The development of the emission weighting and the method used to integrate the weighting into the traffic variable is transferrable to all other LUR models which have a traffic variable with limited detail on vehicle fleet composition as it retains the link with the original model methodology (i.e. if the vehicle fleet breakdown on a route is the same as the national vehicle fleet the overall weighting is 1, if the fleet has a greater proportion of heavier emitting vehicles the overall weighting is above 1 and if the fleet has newer and lower emitting vehicles the overall weighting is below 1). This ensures that the regression coefficients developed within the model are unaffected by the inclusion of the additional detail on the vehicle fleet. This introduces a new function in the WS-LUR model which can be used to assess mitigation measures targeting changes in the vehicle fleet breakdown and determine the resultant changes in NO_2 concentrations.

In Chapter 4, the enhanced WS-LUR model was developed within the Excel software. The availability of the model within easily accessible software that requires very little training for modellers has additional benefits in comparison to the process of running LUR models within GIS software. To generate maps / concentrations within GIS software, a significant amount of data processing is required and familiarity with GIS software is necessary to overlay all the information required and carry out the calculations. This model only requires the input data for the variables and all calculations for NO_2 concentrations are automatically completed by the model. This model was developed with two methods of calculation, a pre-set approach and a manual entry approach. The pre-set approach can generate calculations in a relatively short amount of time for a number of years (2016 to 2018) using data saved within the background of the model. The manual entry approach requests mandatory input data of the modeller and generates concentration estimates in a relatively short amount of time when analysing a time period outside of 2016 to 2018.

The model can also be utilised to assess the impacts of mitigation measures targeting one or a number of variables within the model. The model simplifies the process of analysing pre- and post-mitigation measure scenarios as the modeller can select areas of interest instead of generating a standard map covering a larger region, which significantly reduces processing time. Once pre-mitigation measure variable values are included in the model only the variable values affected by the mitigation measure need to be revised when assessing a post-mitigation measure scenario, which significantly reduces pre-processing time and data errors. The development of the model within Excel also makes it easier to distribute the model to other modellers and researchers interested in estimating pollution concentrations as it does not require significant computing power or memory in comparison to other modelling approaches, such as air dispersion modelling described in Section 2.6.1. Chapter 5 presents the results of the validation of the model developed in Chapters 3 and 4, which captured approximately 76% of the spatial variability of NO_2 and modelled concentrations to within approximately 17% of measured concentrations across a wide range of locations.

In Chapter 5, the performance of the enhanced WS-LUR model was assessed during the 1st COVID lockdown period. The modelled concentrations were on average within 44% of the measured concentrations across all modelled locations and the higher percentages for differences between modelled and measured concentrations were attributed to the lower concentrations experienced during the COVID lockdown period. This was a unique study which utilised a WS-LUR model that had been demonstrated to accurately estimate concentrations during normal conditions, to assess the accuracy of the model under the unique conditions presented by the COVID lockdown period. The benefit of analysing model performance during these conditions was the availability of measured hourly NO_2 concentrations which facilitated the comparison of modelled and measured concentrations to validate the model under abnormal conditions. This provided confidence in the use of the model to estimate concentrations under a wider range of conditions. The analysis also provided an opportunity to assess the accuracy of the model to predict changes in concentrations due to changes in individual predictor variables by again comparing modelled concentration differences and measured concentration differences. The potential of the model to accurately estimate concentration changes due to mitigation measures was confirmed by this analysis.

The development of the WS-LUR model to include detail of the vehicle fleet breakdown provides an opportunity to use the model to assess the impacts of mitigation measures, which focus not only on the variables within the model but impact particular vehicle types. The use of the WS-LUR model within Chapter 6 was useful to analyse the effects on pollutant concentrations at specific locations that were of interest in each of the mitigation scenarios. The Blanchardstown business hub relocation achieved concentration reductions across the majority of modelled locations, reductions which were in the range of 0.0 $\mu g/m^3$ and 1.9 $\mu g/m^3$. Modelled locations within the region of the new business hub (Kildare Town) also achieved positive results with minor reductions in concentrations, achieved mainly by the changes in traffic flows. The public service vehicles diesel removal mitigation measure focused on modelled locations within the Greater Dublin Area as this is the type of location where the majority of these vehicle types operate. This mitigation measure achieved reductions in the range of 0.3 $\mu g/m^3$ and 1.9 $\mu g/m^3$. The Cork Ring Road scenario achieved reductions in the range of 0.0 $\mu g/m^3$ and 1.3 $\mu g/m^3$ with the heaviest polluted locations in the pre-mitigation scenario all experiencing reductions and minor changes in concentrations, which is a major benefit of this mitigation measure. As expected, the increases were all in locations in close proximity to the ring road and localised mitigation options were discussed for these locations to achieve the greatest benefits from this mitigation measure (reduce concentrations in current heavily polluted areas and reduce the impacts on locations near the ring road). The LEZ mitigation achieved concentration reductions across the majority of modelled locations, with reductions in the range of 0.0 $\mu g/m^3$ and 3.0 $\mu g/m^3$. The comparison of pre- and post-mitigation scenarios was based on 2019 and a future year (2030), therefore, this mitigation measure achieved significant reductions in concentrations despite the growth that would be expected in future traffic flows. All of the mitigation measures produced positive results in areas which currently experience high levels of NO_2 concentrations and mitigation measures such as those identified in this research are critical in future to ensure compliance with the Directive 2008/50/EC limits and achieve the reduced limits set by the World Health Organisation.

The meteorological (wind speeds and directional proportions) and land use data was the same for all of the mitigation measures and was the same for the pre- and post-mitigation scenarios as none of the measures targeted these variables. The traffic (road density and IDWVKT) data for all of the mitigation measures were based on outputs from a traffic model. The Cork Ring Road mitigation measure traffic data was sourced from a different NTA model (south region model) compared to the traffic data for all of the other mitigation measures (east region model). The traffic data used for the pre- and post-mitigation scenarios were different in each of the mitigation measures (Cork Ring Road, Blanchardstown business hub relocation and Dublin LEZ) apart from the public service vehicles diesel removal measure. The same traffic data was used for both the pre- and post-mitigation scenarios in this measure but the vehicle fleet breakdown for the SPSVs and LPSVs were changed to replace diesel with electric in the post-mitigation scenario which altered the weighting of the vehicle flows in the IDWVKT. For the Cork Ring Road, Blanchardstown business hub relocation and Dublin LEZ mitigation measures, the conditions set in the traffic modelling to produce the post-mitigation flows were different. The Cork Ring Road had an additional route(s) added to the model which would affect both the road density and IDWVKT variables. The Blanchardstown business hub relocation scenario moved trip attractions from one location to another and the Dublin LEZ scenario introduced a charge on entering particular zone(s) within the city. The commercial properties data was the same for the pre- and post-mitigation scenarios in each of the Cork Ring Road, Dublin LEZ and public service vehicle diesel removal measures. In the Blanchardstown business hub relocation, commercial properties were moved from the Blanchardstown area to Kildare Town and the surrounding area.

Focusing on the results achieved in the mitigation measure analysis, the St. John’s Road modelled location experienced the largest reduction in all of the Leinster based mitigation measures (Dublin LEZ, Blanchardstown business hub relocation and public service vehicle diesel removal). The other Dublin City Centre locations (Winetavern Street, Pearse Street and Coleraine Street) were in the top 5 in terms of concentration reductions in each of the Leinster based measures. The Davitt Road and Dun Laoghaire locations showed significant increases in both the Dublin LEZ and Blanchardstown business hub relocation. This indicates that these locations are impacted significantly due to their location relative to major routes into the city and that these routes are located on the predominant wind direction side of the location. The public service vehicle diesel removal was the only mitigation measure which achieved reductions across all locations and they were all significant reductions throughout. The location of the mitigation measures relative to modelled locations had a significant impact on the magnitude of the result achieved, with changes in the predominant wind directions (west and southwest) having a heavier weighting than other wind directional sectors as experienced in the Cork Ring Road, Dublin LEZ and Blanchardstown business hub scenarios. Significant reductions were experienced in locations close to focal point of each of the mitigation measures, such as the south ring road and city center in the Cork Ring Road scenario, the Blanchardstown area in the business hub relocation scenario and the Dublin City Centre in the Dublin LEZ and public service vehicle diesel removal scenarios.

The reductions achieved in the Blanchardstown business hub relocation, public service vehicle diesel removal and Dublin LEZ scenarios at the Dublin City Centre modelled locations were significant reductions as these modelled locations continue to experience annual mean concentrations close to 40 $\mu g/m^3$, which is the annual mean limit set in the Directive 2008/50/EC (European Union, 2008), and are above the revised WHO annual limit of 10 μg / m^3 (World Health Organisation, 2021). This revision of the limit by the WHO is a challenge at the majority of locations in Ireland as only a small number of locations are below the new limit and these locations are primarily in rural environments. This highlights the need to focus on mitigation measures such as the Blanchardstown Business Hub, LEZ and removing diesel powered vehicles from the public service vehicles, which can improve air quality over a wider region.

In terms of the Blanchardstown Business Hub Relocation mitigation measure, additional benefits would be expected; such as reducing the number of people travelling to this location and being exposed to high levels of pollution on a daily basis. It would also benefit people permanently living in Blanchardstown and the largely residential surrounding area as the traffic in this location would be expected to reduce considerably. The changes in air quality in Kildare Town are minimal despite the additional trip attractions in the area. This measure would benefit the population of Kildare Town economically with the introduction of a number of businesses in the area which would provide additional employment opportunities in the region. This would be expected to improve the work life balance of the commuter population (Kildare and surrounding counties) with shorter commuting distances / time as they would no longer need to travel into areas of significant congestion such as the Greater Dublin Area. This mitigation measure would move job attractions from areas which are in the upper range of housing / rent prices to areas of more reasonably priced accommodation which would benefit the cost of living for the working population.

The removal of diesel fuelled vehicles from the SPSV and LPSV fleets has the potential to considerably reduce NO_2 concentrations across urban areas where pollution is typically greater and larger populations are exposed to these pollutants, whilst smaller reductions are experienced in suburban and rural areas where SPSV and LPSV numbers and the distance travelled by these vehicles are less. SPSVs and LPSVs are only 1.2% of the national vehicle fleet and yet major reductions in NO_2 concentrations can be achieved by promoting greener fuel options within a small proportion of the vehicle fleet which are predominantly business owned and government funded vehicles.

The ring road mitigation measure in Cork did reduce NO_2 concentrations for sites within the city centre and south of the city. NO_2 concentration increases were experienced at areas alongside the new ring road alignment, but all of these locations were still below the revised WHO annual limit of 10μg/m^3 after the ring road was implemented. Locations within 5km of the ring road only experienced minor increases in NO_2. These increases were due to a combination of both the traffic on the new ring road and the predominant wind direction in this area, which carried emissions from the ring road towards the city. Therefore, mitigating measures such as barriers in combination with the ring road, could aim to prevent the dispersion of pollution from the new route. This solution would aim to benefit both city centre locations and areas in close proximity to the ring road as traffic would be reduced on city centre streets and the spread of pollution from vehicles on the ring road would be contained.

7.2. Limitations of this Research

The selection of the variables in the WS-LUR model followed a similar procedure to other LUR models identified in Section 2.6.2. The initial model was created using the variable with the highest R^2 value. Then additional predictor variables were consecutively included, but were only retained if the overall R^2 value increased by at least 1%, the direction of effect of the new variable is as a priori defined, and the new variable does not result in a change in the direction of effect of the previously included variables (Naughton et al., 2018). Therefore, variables which may have minor contributions to NO_2 nationwide or that may contribute NO_2 at only a small number of locations may be excluded from the concentration estimate due to the above criteria. This potentially impacted concentration estimates at monitoring sites such as St. John’s Road and Ringsend across a number of the analyses. Factors which were identified at the St. John's Road site that may contribute to NO_2 pollution include train traffic entering and leaving Heuston train station, numerous areas where engine idling could occur such as taxi ranks and bus stops and a traffic signalised junction / crossing where queuing and lower traffic speeds are common. Potential sources of NO_2 near the Ringsend station not captured by the model include the Poolbeg Generating Station, boat traffic entering Dublin Port and vehicular traffic such as HGVs in Dublin Port (ESB Energy International, 2013; European Space Agency, 2020). Traffic within Dublin Port is not captured as it is not part of the local authority or Transport Infrastructure Ireland road network.

Similar to all other models, the accuracy of the concentration estimation in the enhanced WS-LUR model is dependent on the accuracy of the input data for each of the variables. Therefore, the more accurate the vehicle fleet breakdown data reflects the fleet at a study location and the surrounding routes the better the model is able to estimate pollution concentrations. The vehicle fleet breakdown calculated for each analysis represented the national vehicle fleet based on the the Irish Bulletin of Vehicle and Driver Statistics by the Department of Transport, Tourism and Sport (Department of Transport, Tourism and Sport, 2011; Department of Transport, Tourism and Sport, 2018; Department of Transport, Tourism and Sport, 2019). This would assume that the breakdown by Euro Class and fuel type were the same on all routes and across all regions whilst in reality this may not be the case. Studies were carried out by the Department of Transport, Tourism and Sport on the vehicle fleet breakdown within the five major cities in Ireland (Department of Transport, Tourism and Sport & Systra, 2020) and these statistics were applied in the small city zones where the studies were carried out. The Euro Class and fuel type breakdown for the national vehicle fleet were applied to all remaining areas outside of these city zones. Considering both the concentration estimates and the standard errors calculated in the model validation study in Chapter 5, on average the modelled concentrations were within 17% of the measured concentrations across all monitoring station locations which aligns with the accuracy achieved by the model (cross validation R^2 of approximately 76%). The approach used to integrate a weighting based on the emission rate of vehicles ensures the link with the original model is retained and therefore the accuracy of the model would not be affected significantly by the inclusion of a function which accounts for vehicle fleet breakdown.

In the COVID lockdown analysis, transport model outputs of the COVID lockdown period were not available. Therefore, traffic counter data which was sourced from the Transport Infrastructure Ireland traffic counter database was used for the major routes (Transport Infrastructure Ireland, 2022). These counters continuously record data throughout the year for all major routes (motorway and national standard), therefore, were available for the entire COVID lockdown period considered in this analysis. The local authorities are responsible for the traffic counts on all minor routes located within their city / county and are not readily available. The procedure for traffic counts by the local authorities do no record flows for long periods of time and take place during neutral months in the year (such as November and later February / early March, months not affected by public holidays, school holidays and holiday season in summer and winter) and neutral days of the week (such as Tuesdays or Thursday). Therefore, a full dataset for minor routes flows would not be available for the COVID lockdown period. The effects of excluding the minor route flows from the analysis was quantified in terms of concentrations changes within the research described in Chapter 5 to account for this limitation.

7.3. Future Research

A small number of locations such as the Ringsend and St. John’s Road modelled locations were impacted by other NO_2 pollution sources not captured by the WS-LUR model within the model validation analysis and COVID analysis. These pollution sources included the Poolbeg Generating Station, boat traffic entering Dublin Port, vehicular traffic in Dublin Port, areas of engine idling (taxi ranks and bus stops), train traffic entering / leaving Heuston Station and traffic queuing / lower speed areas (traffic signalised junctions / crossings). A number of these sources are unique to these locations therefore altering the WS-LUR equation across the entire country would impact the results of other locations. To ensure the accuracy of the model is not impacted by accounting for these other pollution sources, the enhanced WS-LUR equation developed within this research would be applied to all locations in the country and in close proximity to locations such as St. John’s Road and Ringsend, the potential to introduce an additional variable(s) which would account for these other pollution sources should be examined. This would include determing the regression coefficients and buffer sizes for these new variables.

The operating temperature of vehicle engines can have a significant impact on the emission rates, therefore the integrated transport, emissions and air quality modelling approach identified in this research could be extended to account for these conditions. The flows on each of the routes could be split based on cold or hot operating temperatures through the use of transport modelling which utilises origin and attractions to model traffic flows. Therefore the distance / time required to transition from cold to hot engine operating temperatures could be researched and incorporated into the IDWVKT variable in the enhanced WS-LUR model, similar to the weighting approach used for the emission rates of various vehicle types within this project.

The results achieved by the model for mitigation measures could be used to expand on an epidemiological study which links NO_2 exposure to various health effects by determining the potential reductions in the number of cases of various health effects that may be achieved if mitigation measures are implemented. This could be achieved by modelling the reductions in NO_2 concentrations from various mitigation measures and utilising this information for an epidemiological study population. The results could be interpreted based on the reductions in the number of health effect cases that could be experienced and / or determining the extent to which the link between NO_2 exposure and various health effects can be reduced due to the changes in concentrations.

The results achieved by the public service vehicle diesel removal mitigation measure were significant as it produced a blanket reduction across the Greater Dublin Area, which experiences the highest levels of pollution in Ireland. The magnitude of the reductions were also significant as these positive results were achieved by targeting a small proportion of the national vehicle fleet, which are predominantly government owned or regulated by a government agency (0.77% of the national vehicle fleet are SPSVs and 0.41% of the national vehicle fleet are LPSVs). The National Transport Authority has proposed to increase the fare for the SPSVs due to the increasing operating costs related to an SPSV (National Transport Authority, 2022). The Sustainable Energy Authority of Ireland has a car comparison calculator which identifies the annual fuel / energy cost and the 10 year total cost of ownership for a wide range of vehicles (Sustainable Energy Authority of Ireland, 2022). By comparing a diesel powered vehicle with the equivalent battery electric vehicle, it was found that the annual energy cost is approximately €1 200 less and the total cost of ownership (includes price, tax, maintenance, fuel, etc.) is approximately €4 000 less for the electric vehicle. Therefore, the recommendation would be to transition to electric vehicles to firstly improve air quality but also to improve the overall cost of ownership of SPSVs. This would reduce the impact of increasing fuel prices on owners and would ensure that SPSV fare increases would not be required or would be less than proposed, and therefore would not impact the number of people currently using the public service vehicles. This mitigation measure would require further expansion of the existing charging point network to accommodate the increased demand. A large proportion of the existing charging point network for electric vehicles in Ireland are located in urban districts and city centres (ESB, 2021) which aligns with the demand from the small public service vehicle and large public service vehicle fleets, which primarily operate in urban areas. Locations for new charging points would probably vary from those in the current network, which are primarily at public parking locations, as the key locations for the small public service vehicles and large public service vehicles would be in areas where they would be idle between journeys such as taxi ranks and bus terminals.

The Ring Road mitigation measure identified a number of locations in close proximity to the ring road alignment which would experience increases in NO_2 pollution due to the traffic which would utilise the ring road where previously they would have travelled through the city or to the east and south of the city. The mitigation measure did result in reductions in the most heavily polluted areas of the city (south / east of the city and along the South Link Road). The ring road provided an alternative route around the city centre which resulted in reductions in the number of cars, LGVs and HGVs travelling through the majority of the city centre routes. Areas where the ring road was located within the predominant wind direction sector experienced increases in NO_2 pollution. This mitigation measure could be expanded to include barriers which would attempt to reduce the dispersion of the pollutant to these areas in close proximity to the ring road. This would require an in-depth analysis of the pollutant dispersion along the ring road and also identifying the best barrier design, in terms of barrier heights and sections of routes where barriers are required, to reduce the dispersion of the pollutant. The recommendation from this mitigation measure would be to invest in the road network to provide alternative routes around a city / town, which would reduce pollution and the number of vehicles within the city centre region. Visual and noise impact mitigation measures within tranportation projects could potentially also act as air quality mitigation by reducing the dispersion of the pollutants using barriers and / or landscaping.

The Blanchardstown Business Hub Relocation mitigation measure identified the significant improvements in air quality that can be achieved by relocating businesses to an area which is more central to the workforce and therefore reduces the overall distance travelled. Significant reductions in air pollution were experienced both in the Blanchardstown region and across the wider Greater Dublin Area. A significant reduction was modelled at one of the locations in Kildare Town region and the changes at the other two locatios were minimal, highlighting that it is possible to improve air quality both in the original and new business locations with this type of mitigation measure. This mitigation measure also highlights the importance of site selection for the development of new businesses. The recommendation would be to prioritise areas outside of the major cities for new businesses / developments and this could be achieved by identifying areas with a significant number of people who are currently unemployed and / or are commuting significant distances for work and these areas should be identified as the best locations for the development of new businesses in Ireland. Also the areas which have the least number of active businesses should also be prioritised in this analysis to ensure the project is not only successful in reducing air quality in currently heavily polluted areas but also a positive in improving employment rates in disadvantaged areas. One key factor in the selection of site locations would be to avoid areas which are currently experiencing poor air quality as any additional businesses in these areas would attract greater numbers of people and traffic to the area and therefore greater numbers would be affected by the exposure to pollutants. Avoiding these areas as potential new business locations could also potentially improve issues within the housing sector where major cities are currently experiencing significantly high rent and housing prices (Government of Ireland, 2016). The Sustainable Development Goals and the Rebuilding Ireland Action Plan for Housing and Homelessness identified five pillars to improve the housing sector and meet the housing demand of the Irish population (Government of Ireland, 2021; Government of Ireland, 2016). One of the pillars is to improve the rental sector by developing a scheme which makes renting affordable, encouraging construction of rental properties and supporting the provision of student accommodation to reduce the demand on the private rental sector. The Blanchardstown business hub relocation can relocate the demand for private rental properties and / or reduce the overall demand for private rental properties as the new business location will be located closer to the permanent residence of the working population. The reduction of attractions in these areas would warrant an analysis of the potential improvements in the housing sector. The enhanced WS-LUR model can play a key role in determining the best locations for future development / relocating businesses as the variables in the model align with the changes that would need to be modelled for these scenarios (e.g. the number of commercial properties, changes in traffic flows and changes in land use). The modelled changes in air pollution using the enhanced WS-LUR can be used in the planning / decision making process for the ideal locations for these developments. A further recommendation for policies on business developments was identified within the results of the COVID analysis. A work from home scenario should be promoted with jobs that can be carried out from home as significant improvements in air quality can be achieved.

8. Conclusion

This chapter concludes the research by providing a summary of all the work described within this thesis, discussing the main contributions of this work towards LUR modelling such as the integration of transportation, emissions and LUR modelling and the use of LUR models in mitigation measure analysis. The research carried out within this thesis provides a significant amount of detail which would assist in improving policies within the transport and business sectors, investment in infrastructure and the importance of air quality modelling, modelling methods and air quality monitoring networks.

This research developed an enhanced WS-LUR model that can account for vehicle fleet breakdown within the traffic variables to estimate NO_2 concentrations at any location in Ireland, as described in Chapter 3. This ensured that flows of heavier emitting vehicles had a larger weighting than smaller vehicles along each of the routes. It would also demonstrate the importance of accounting for vehicle fleet breakdown on routes with larger numbers of HGVs and LPSVs are likely to generate higher levels of NO_2 than other routes. The development of an emission weighting for vehicle types within the traffic variables of the enhanced WS-LUR model introduces an additional function within the model which can analyse mitigation measures which target the vehicle fleet breakdown.

The model was developed within the Excel software and had two modelling approaches, a pre-set approach and a manual entry approach, as presented in Chapter 4. The pre-set approach in the model was developed with complete sets of input data for 2016 to 2018 prepared for use in the research described in Chapters 3, 4 and 5. This approach is available for use in future modelling studies and will require no data processing to generate NO_2 concentrations at any location for this time period. The manual entry approach allows modellers to collect data for a study location and input the values directly into the model to quickly generate an NO_2 concentration if analysing a time period outside of 2016 to 2018.

The model was validated by comparing modelled concentrations to measured concentrations across various locations in Ireland. A further analysis was carried out on the accuracy of the model, by estimating concentrations for a unique scenario / environment, specifically the 1st COVID lockdown. The methodology and results of these model validation and analysis studies are presented in Chapter 5, where modelled concentrations from this scenario were compared with measured concentrations during the lockdown period.

This research also analysed a number of mitigation measures, using the enhanced model, to determine the potential improvements in air quality that could be achieved throughout Ireland using approaches that have been employed in other international settings. The mitigation measures identified in this analysis targeted one or a number of the predictor variables within the WS-LUR model and these included:

- Blanchardstown Business Hub Relocation – relocation of commercial properties (attractions) and resultant alteration to traffic flows;
- SPSV and LPSV Diesel Removal – transitioning from predominantly diesel powered vehicle fleets to greener fuel options (electric vehicles);
- Cork Ring Road – providing alternate routes for traffic flows to reduce congestion and emissions in city centre roads and streets;
- Dublin LEZ – influencing traffic mode choice by implementing a fee to enter the city centre.

The mitigation measures were analysed by comparing modelled pre-mitigation measures concentrations with post-mitigation measure concentrations to determine the changes in NO_2 concentrations across a number of locations.