HOW EFFECTIVE ARE TRAFFIC LIMITING MEASURES AT IMPROVING AIR QUALITY?
A STUDY OF THE MALTESE CONTEXT

authored by

Samuel Cilia

Dissertation submitted to the Faculty for the Built Environment, University of Malta, as part of the requirements for the attainment of the degree of Master of Engineering

submitted in

June 2024

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I dedicate this dissertation to the cherished
memory of my grandparents.

ACKNOWLEDGEMENTS

This Master's dissertation was written during scholastic year 2023/24 of the Master of Engineering (Civil Engineering) course at the University of Malta.

I would like to express my gratitude to everyone that has supported me in completing this dissertation. Firstly, I would like to thank my supervisor, Dr. Odette Lewis, for being a constant help throughout this process, but whose mentorship and encouragement fostered my passion towards civil engineering and the transportation field.

I also want to extend my appreciation to Dr. Paul Gauci and Profs. Alfred Micallef for providing invaluable assistance and always being supportive throughout this whole process. I would also like to mention Profs. Emmanuel Sinagra, and professionals from ERA, TM and IM who have also been of great help.

Additionally, I am sincerely grateful to my friends and course-mates who have made my university experience that much more memorable and fulfilling. Particularly, I would like to thank Mr.John Schembri and Mr.Ryan Worley, who, not only helped me during this process, but whose friendship was a source of encouragement, inspiration, and support throughout these past years.

Finally, I want to mention my parents – Frank and Joanne, and sister – Mariella, whose unconditional love and support throughout my studies I will forever appreciate.

I take full responsibility for any shortcomings in this dissertation.

ABSTRACT

The urban environment in Malta faces escalating challenges resulting from population growth and an increase in vehicular traffic, congestion and poor air quality. Consideration is given to the traffic and air quality situation in the Maltese context, and the adverse health effects linked to traffic generated air pollution. This research addresses these issues by exploring the application and effectiveness of traffic limiting measures as a means to improve air quality.

By investigating international best practices and existing local policies, it was found that the application of ‘push’ measures was a recommended approach to reduce private vehicle usage and promote sustainable transportation alternatives. The methodology involved applying and testing similar measures within a defined section of the Maltese road network.

The main testing methodology utilised a digital toolset, composed of microsimulation traffic modelling, emission modelling and air dispersion modelling. A microsimulation traffic model of a selected area in Malta was constructed to simulate the traffic situation before and after the implementation of proposed traffic limiting measures. Subsequently, data extracted from the traffic model was used in emission and air dispersion modelling software to evaluate the effectiveness of the proposed strategies in improving air quality.

The modelling results show that the tested measures, which involved the limiting of private vehicle use and access, saw a decline in traffic performance and/or small variations in pollutant concentrations. Through this analysis, the study concluded that introducing minor-scale strategies that simply limit vehicle traffic on small parts of the road network can result in negligible impact on air quality. Additionally, the importance of the vehicle fleet composition was shown to be also vital. In future, consideration should be given to testing broader strategies that improve capacity for other, cleaner modes of transport, along with limiting access to polluting private vehicles.

Ultimately, the modelling process outlined in this study can be used by decision makers to test other types of measures aimed at reducing traffic-generated emissions, in order to find the most effective strategies, especially with the introduction of more stringent air quality standards.

KEY WORDS:

Traffic Limiting Measures, Microsimulation Traffic Modelling, Emission Modelling, Air Dispersion Modelling, Air Quality Assessment

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ABBREVIATIONS

Abbreviation	**Meaning**
AAQD	Ambient Air Quality Directive
ANPR	Automatic Number Plate Recognition
CBD	Central Business District
CIVITAS	CIty-VITAlity-Sustainability
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
COPERT	Computer Programme to calculate Emissions from Road Transport
CVA	Controlled Vehicular Access
EAMA	European Automobile Manufacturers' Association
EEA	European Environmental Agency
EF	Emission Factor
EPHA	European Public Health Alliance
EPRS	European Parliamentary Research Service
ERA	Environment and Resources Authority
ERMES	European Research on Mobile Emission Sources
EU	European Union
EV	Electric Vehicle
FHWA	Federal Highway Administration
GDP	Gross Domestic Product
HBEFA	HandBook on Emissions FActors for road transport
Hg	Gaseous Mercury
ICE-V	Internal Combustion Engine Vehicles
IM	Infrastructure Malta
ITS	Institute for Transport Studies
LEZ	Low Emission Zone
MEPA	Malta Environment and Planning Authority
MPT	Malta Public Transport
NEC	National Emissions reduction Commitment
NO_X	Nitrogen Oxides
NO_2	Nitrogen Dioxide

Abbreviation	**Meaning**
NSO	National Statistics Office
NTM	National Transport Model
O3	Ozone
OECD	Organisation for Economic Co-operation and Development
PM	Particulate Matter
PM_{10}	Particulate Matter 10 microns
$PM_{2.5}$	Particulate Matter 2.5 microns
SO_2	Sulphur Dioxide
TEN-T	Trans-European Transport Network
TfL	Transport for London
TM	Transport Malta
ULEZ	Ultra Low Emission Zone
VOC	Volatile Organic Compounds
VRT	Vehicle Roadworthiness Test
WHO	World Health Organisation

CHAPTER 1 - INTRODUCTION

1.1. Overview

1.1.1. Maltese Context

At of the end of 2022, Malta's population increased to 542,051 people, cementing its status as the country that has the highest population density in the EU, that of 1,720 people per square kilometre (NSO, 2023b). Unsurprisingly, the recently issued Transport Statistics 2023 (NSO, 2023a) shows that the number of vehicles on Maltese roads has also increased substantially over the years. Indeed, by the end of 2021 the figure was 413,019 (p.123). This means that Malta has 1,517 vehicles for every 1,000 licensed drivers. Another trend documented in the publication shows that the fleet is being more intensely used in terms of kilometres travelled.

In terms of fleet composition, the same report shows that petrol and diesel powered vehicles make up the vast majority of the vehicle stock, 59.2% and 37.8% respectively. Vehicles that run on an alternative energy source make up just 3%. Additionally, the average age of a motor vehicle was 15.39 years in 2021, with the average age of passenger vehicles being slightly lower at 14.98 years, this figure being higher than the EU average of 12 years (EAMA, 2023).

The 2021 National Household Travel Survey goes to further prove the Maltese obsession with private vehicles. For instance, the survey found that, on average, the private car was used for 84.3% of all trips, with buses, walking and cycling making up 5.6%, 7.1% and 0.7% respectively (NSO, 2022). As a result, congestion has become worse than ever before, with air pollution, noise pollution and road safety following similar negative trends. According to the European Commission (2023b) , these issues are costing the country €400 million a year, or 3.6% of GDP. It was noted that while air pollution is not increasing with GDP, NOx and PM_{10} pollutants are still present at high levels.

1.1.2. Health Effects

According to the European Environmental Agency (EEA, 2013), air pollution can be defined as the existence of certain pollutants in the atmosphere that are at concentrated levels which negatively affect human health, the environment, and cultural heritage. Over the years, extensive research has been done on the topic of air pollution, particularly on how exposure can adversely impact human health. Many of these studies have expressly linked exposure to certain air pollutants with a rise in hospitalisations and increased risk of mortality. This is mostly attributed to a range of health conditions that can be experienced such as nausea, difficulty breathing, skin irritation, and even cancer (Kampa & Castanas, 2008).

Road transport continues to be a significant contributor to some of the most harmful air pollutants, particularly nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter

(PM). Vehicle emissions are of particular concern in urban areas when compared to other emission sources as these emissions occur where people live and work. This means that vehicle emissions affect a higher proportion of the population than any other source, typically located away from urban centres (EEA, 2016).

As outlined in the previous section, Malta's urban environment has been subject to high degrees of traffic congestion due to the recent increases in population and vehicle numbers. This brings with it adverse effects like increased noise pollution, road safety issues, and increased air pollution. A study on the state of health in the European Union (EU) has shown that a substantial proportion of the Maltese population experiences higher rates of asthma and chronic obstructive pulmonary disease (COPD) than other EU populations, despite having a similar 4% of deaths attributed to air pollution (OECD, 2021).

Several previous research initiatives conducted in Malta (Balzan & Bonnici, 2004; Montefort et al., 1998) document a direct correlation between vehicle emissions in urban areas and higher rates of respiratory issues like asthma. According to more recent information coming from the Maltese Ministry for Health (Calleja, 2023), the rate of asthma hospitalisations has been increasing over the last decade. The data shows that a third of admittances originated from localities in the centre of the country, including Birkirkara, Gżira, Ħamrun, Msida, Pieta, Qormi, St Julian's, Swieqi, and Sliema. This further indicates that there is a correlation between the high concentrations of traffic and adverse health effects (Calleja, 2023).

1.1.3. Perceptions on Air Quality in Malta

A survey conducted by the Environment & Resources Authority (ERA, 2023) on air quality in Malta revealed that most respondents are concerned about this issue, with traffic and exhaust emissions being identified as the primary causes of pollution. While respondents expressed less concern about air quality in their own localities, the majority attribute worse air quality to traffic, particularly in the Northern and Southern Harbour regions. Despite their concerns, respondents were divided on effective short-term solutions to improve air quality, and a significant majority preferred using personal vehicles for their daily commutes. Additionally, over half of the respondents indicated a willingness to switch to a less polluting vehicle, if the government provided incentives.

In a Eurobarometer survey, a majority of Maltese people were found concerned about the decline in air quality and its impact on their health, believing it has worsened in the past decade. Respiratory diseases, asthma, and heart disease are the top health concerns attributed to poor air quality among Maltese respondents. Low emission transport modes are favoured as the most effective solution to address air pollution, while penalties for those responsible for breaching air quality standards are also supported. However, both public authorities and employers are perceived as not doing enough to promote good air quality and enable sustainable commuting practices, respectively (European Commission, 2022).

1.2. Mitigation Strategy

In this dissertation, the focus is on the application of traffic limiting measures as the main traffic emission mitigation strategy. Vehicle congestion has been an issue in urban areas for a long time, with this being the main contributor to poor air quality in urban areas globally (EEA, 2016). Therefore, one can find many approaches taken by different jurisdictions around the world that have had to deal with air pollution caused by congestion. As a result of all these existent policy solutions, according to Marsden and Stead (2011), it is very often the case that city authorities and national governments simply copy these measures from others, which they dub ‘policy transfer’. In their view, different environments demand different policy responses, meaning that measures should be tested before their implementation in a jurisdiction with a different context.

1.3. Research Background

1.3.1. Objectives

It is the aim of this study to assess how policies affecting traffic behaviour have an impact on one of its negative side effects, degradation of air quality. Specifically, the research focuses on studying the effectiveness of traffic limiting measures using traffic congestion and air quality metrics. This is to be achieved by using microsimulation traffic and air quality modelling software.

The process shall involve the construction of a digital, microsimulation traffic model of an area in Malta, through which one can conduct a comparative analysis of the existing traffic situation (i.e., baseline conditions) and the implementation of the above-mentioned limiting measures (i.e., modified conditions). These results shall then be used in emission modelling and air dispersion modelling software packages to provide insights into the effects of these traffic behaviour changes on air quality.

In addition to modelling, this study also required a review of directives, laws, regulations, and standards designed to control unhealthy gaseous and particulate emissions. Moreover, international and Maltese measures aimed at combating traffic and its associated emissions shall also be documented.

This dissertation, therefore, aims to show how traffic and emission modelling tools can be used to test the performance of traffic limiting measures, and their associated impact on air quality. In other words, the process adopted to test these measures digitally before their being considered for implementation in the real-world is to be described and evaluated.

The procedure to attain the above-mentioned objectives involves:

- Documentation of a range of traffic limiting and emission reducing measures.
- Selection of an ideal study area.
- Collection of observed traffic data at strategic locations in the study area network, together with data generated through Transport Malta's national macrosimulation model (referred to as the National Transport Model) (Transport Malta, 2024).
- Modelling of the road network in the selected area and traffic passing through this network using microsimulation modelling software.
- Extracting, documenting, and use of the traffic model generated data for inputting into the emissions and dispersion models.
- Documentation of results from the traffic, emission, and dispersion models.
- Analysing these results to find the impact of the tested traffic-limiting measures, based on traffic and air quality metrics.

1.3.2. Research Question

How can digital modelling tools, particularly traffic microsimulation, emission, and air dispersion models, be used to develop a framework for assessing the effectiveness of traffic control measures and policies in reducing traffic generated emissions?

1.4. Structure

Chapter 2 involves a review of three important topics: the first describes the effect of vehicle traffic on air quality and the frameworks developed to mitigate it, the second provides insight into different strategies that combat traffic-generated emissions both internationally and nationally, and the third discussing and documents the process of traffic-emission air-quality modelling.

Chapter 3 describes the methodology employed during this research, with the process starting from the site selection and identification of the measures being modelled. The chapter goes on to document the procedure followed during the traffic, emission and air dispersion modelling steps.

Chapter 4 goes into documenting and analysing the results gathered after each modelling step. This chapter also investigates the relationship between the results of one modelling step and its successive step.

Chapter 5 includes an overview of the results and their significance, while also discussing the limitations encountered during the research process. Finally, the chapter discusses possible improvements, recommendations and ideas on how to build upon this research.

CHAPTER 2 - LITERATURE REVIEW

2.1. Overview

As mentioned in the Chapter 1, targeting traffic generated emissions is considered one of the better ways to improve air quality in urban centres. It is evident that governments around the world have taken notice and, consequently, have experimented with such measures with varying degrees of success. It is the aim of this chapter to document different traffic emission reduction initiatives taken abroad, and locally.

This chapter also documents research about the modelling process chain, from traffic modelling to emission and air quality modelling, with the aim of describing each part of the process.

2.2. Vehicle Emissions Impact on Air Quality

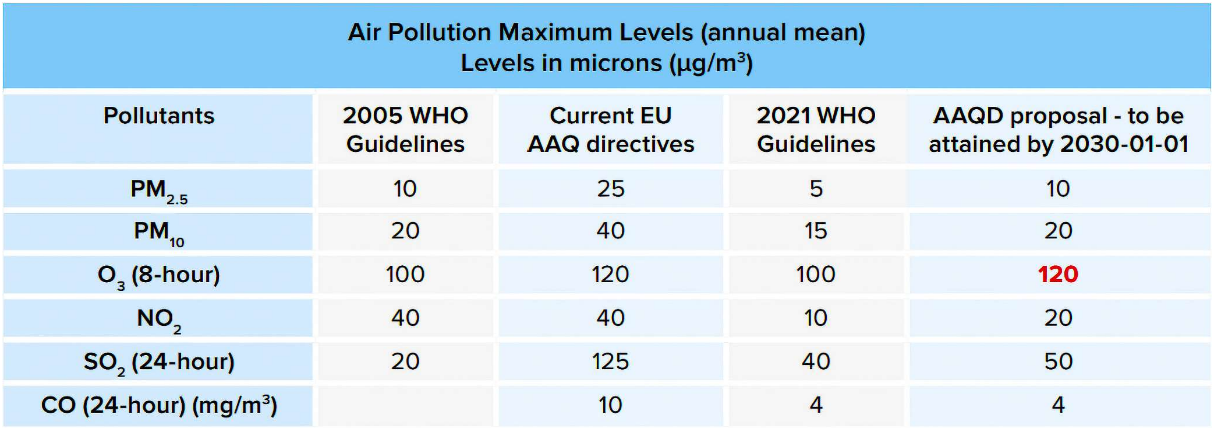
2.2.1. Emission Standards and Regulations

The World Health Organization (WHO, 2024) is the preeminent international body that concerns itself with air quality standards for human health. These guidelines, initially released in 2005, have been an important reference when it comes to regulating vehicle emissions (EPHA, 2023). Recently, the WHO (2021) released an update to these guidelines where safe levels for transport generated pollutants have been reduced, as a result of extensive research showing the harm of even low levels of pollution.

The European Union (EU) has a robust history of regulating air quality (European Commission, 2024), with its current policy framework regarding the subject revolving around three main pillars. The first pillar involves two directives: the 2008 Ambient Air Quality Directive (AAQD) (EUR-Lex, 2008) and the 2004 AAQD (EUR-Lex, 2004). These two directives set air quality standards and pollution measurement criteria that each member state must abide by. The 2004 AAQD focused on the reduction of heavy metal and hydrocarbon pollutants. On the other hand, the 2008 AAQD specifically pushed EU member states to abide by set targets on pollutant concentrations (usually expressed in micrograms per cubic metre, $\mu g/m^3$) like nitrogen oxides (NOx) and particulate matter (PM). When member states exceed these standards, they are directed to develop air quality plans outlining measures to combat the relevant exceedances and air pollution generally (EPRS, 2022).

The 2005 WHO guidelines stood as the benchmark when proposing the AAQD back in 2008. Despite the effectiveness of this legislation in improving air quality compared to 2005 levels, pollutant concentrations remain higher than the recommended WHO figures (T&E, 2023). In fact, exceedances for certain pollutants remain common in EU urban areas. This has prompted the European Commission to propose an update to the AAQDs in 2022, specifically to set a target to reduce air pollution to levels not considered harmful to health and natural ecosystems by 2050, as per the new 2021 WHO guidelines (EPHA, 2023). Figure 1 shows a comparison between WHO guidelines and EU directives when it comes to maximum air pollution limits.

Figure 1. Comparison of WHO and EU air pollution limits (EPHA, 2023)



Air Pollution Maximum Levels (annual mean)
Levels in microns (µg/m^3)

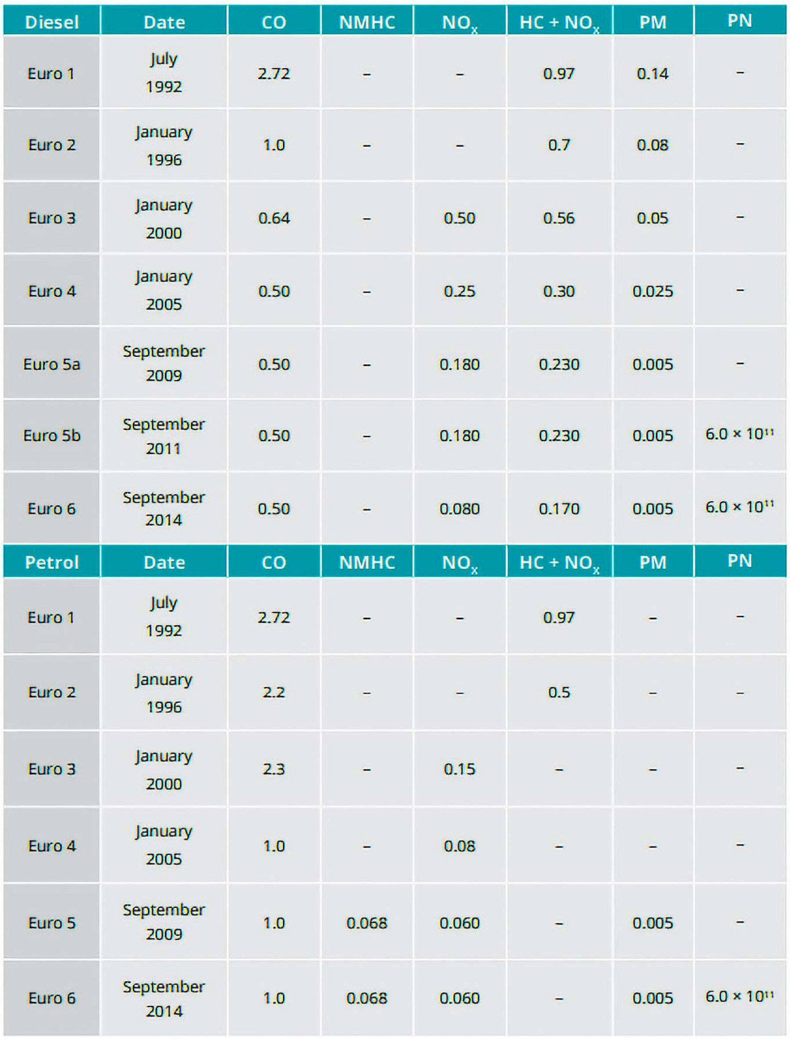
Pollutants	2005 WHO Guidelines	Current EU AAQ directives	2021 WHO Guidelines	AAQD proposal - to be attained by 2030-01-01
$PM_{2.5}$	10	25	5	10
PM_{10}	20	40	15	20
O_3 (8-hour)	100	120	100	**120**
NO_2	40	40	10	20
SO_2 (24-hour)	20	125	40	50
CO (24-hour) (mg/m^3)		10	4	4

Note: [O_3 (ozone) value in red meaning target zone, instead of limit value like the other values]

The second pillar is based on Directive (EU) 2016/2284, also known as the National Emissions reduction Commitments (NEC) Directive (2016). This policy sets national standards (usually expressed in load of pollutant in grams) for five pollutant types: sulphur dioxide, nitrogen oxides, ammonia, non-methane volatile organic compounds and $PM_{2.5}$. In the case of Malta, specific emission reductions for each pollutant based on their 2005 levels must be achieved.

The third pillar focuses on limits to pollution at the source, with specific policies targeting industrial emissions and vehicle exhaust emissions (EPRS, 2022). The EU has implemented vehicle emission reduction policies since the 1970s, with these limits primarily targeting carbon dioxide emissions in the beginning. However, in 1992, a leap occurred in how emission standards were seen and implemented. The 'Euro' vehicle emission standards started with the Euro 1 and have gone through five progressively stricter iterations to end up with Euro 6 standards in 2016 (shown in Figure 2). This means that any new vehicles sold in every EU member state must not generate more pollutants than the Euro 6 set standards. These successive iterations have introduced limits to other pollutants apart from carbon dioxide, including particulate matter and nitrogen oxides (EEA, 2016).

Figure 2. Emission limits (g/km) of the Euro emission standards for passenger vehicles (EEA, 2016)



Diesel	Date	CO	NMHC	NO_x	$HC + NO_x$	PM	PN
Euro 1	July 1992	2.72	–	–	0.97	0.14	–
Euro 2	January 1996	1.0	–	–	0.7	0.08	–
Euro 3	January 2000	0.64	–	0.50	0.56	0.05	–
Euro 4	January 2005	0.50	–	0.25	0.30	0.025	–
Euro 5a	September 2009	0.50	–	0.180	0.230	0.005	–
Euro 5b	September 2011	0.50	–	0.180	0.230	0.005	6.0×10^{11}
Euro 6	September 2014	0.50	–	0.080	0.170	0.005	6.0×10^{11}
Petrol	**Date**	**CO**	**NMHC**	**NO_x**	**$HC + NO_x$**	**PM**	**PN**
Euro 1	July 1992	2.72	–	–	0.97	–	–
Euro 2	January 1996	2.2	–	–	0.5	–	–
Euro 3	January 2000	2.3	–	0.15	–	–	–
Euro 4	January 2005	1.0	–	0.08	–	–	–
Euro 5	September 2009	1.0	0.068	0.060	–	0.005	–
Euro 6	September 2014	1.0	0.068	0.060	–	0.005	6.0×10^{11}

2.2.2. Vehicle Generated Emissions

The adverse effects from vehicle emissions are derived from high concentration levels of pollutants such as particulate matter, sulphur oxides, nitrogen oxides, carbon monoxide, ground level ozone, and heavy metals (EEA, 2013). According to the ERA (ERA, 2019a), the main and most problematic pollutants emitted by diesel/petrol fuelled vehicles in Maltese urban areas are particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides (NOx), and benzene.

Consideration should also be given to what is responsible for the emission of these pollutants. According to the EEA (2016) there are three types of air pollution sources, namely:

- Exhausts of internal combustion engines
- Mechanical abrasion
- Fuels

The first involves emissions from exhausts, which means the emissions generated when a combustion engine processes hydrocarbon fuels. This process is primarily responsible at producing carbon dioxide (CO_2). The second consists of emissions from mechanical abrasion and corrosion of parts. This process is responsible for producing particulate matter and some heavy metal emissions, with deterioration of tyres, brakes, and clutch being primary producers. The third consists of evaporative emissions, meaning emissions that evaporate from the fuel used in the engine. Evaporation can still occur even when the car is parked and its engine turned off, causing the emission of pollutants.

However, Scerri et al. (2023) argue that countries with a climate similar to Malta's are subject to a fourth type of emission. This emission type involves the resuspension of settled dust from road surfaces. Sources of this dust range from construction related activities, marine aerosols and dusts from North Africa that are carried by wind. In fact, Scerri et al. (2023) suggest that electric vehicles would still emit the same amount of PM_{10} as modern internal combustion engine vehicles (ICE-V). This means that the transition to cleaner road transport alternatives would still require attention to be paid to the amount of pollution emitted.

The level of emissions generated by a type of vehicle is generally quantified by emission factors (EF), measured in grams per kilometre (g/km). There are several factors that determine the level of emissions from a vehicle, namely engine type, vehicle speed, fuel type and vehicle age (Lozhkina & Lozhkin, 2016).

2.2.3. Air Quality Data Collection in Malta

The Ambient Air Quality Regulations [S.L. 549.59] (Legislation Malta, 2010) provide the primary air quality framework followed by Maltese regulators and the Courts. These regulations transpose the 2008 AAQD into Maltese Law, officially known as Directive 2008/50/EC (EUR-Lex, 2008).

The 2008 AAQD, apart from regulating air pollution, mandates the setting up and operation of an air quality monitoring system based upon fixed measurements and modelling techniques, as specified in Article 6 (EUR-Lex, 2008). A set of preliminary estimates for pollutant levels was derived from a study conducted by Stacey and Bush (2002). This helped determine the location of the air quality assessment network that had to be established in Malta.

Currently, the Environment and Resources Authority (ERA), the principal environmental regulator in Malta, runs the Air Quality Monitoring Station network, which includes five permanent and one mobile real-time monitoring stations, as well as a network of passive diffusion tubes (Fenech et al., 2021). The real-time monitoring stations are used to determine concentrations of a number of pollutants every fifteen minutes, as required by the Ambient Air Quality Regulations. These include PMs, NOx, O_3, VOCs, SO_2, Hg, and CO (ERA, 2020).

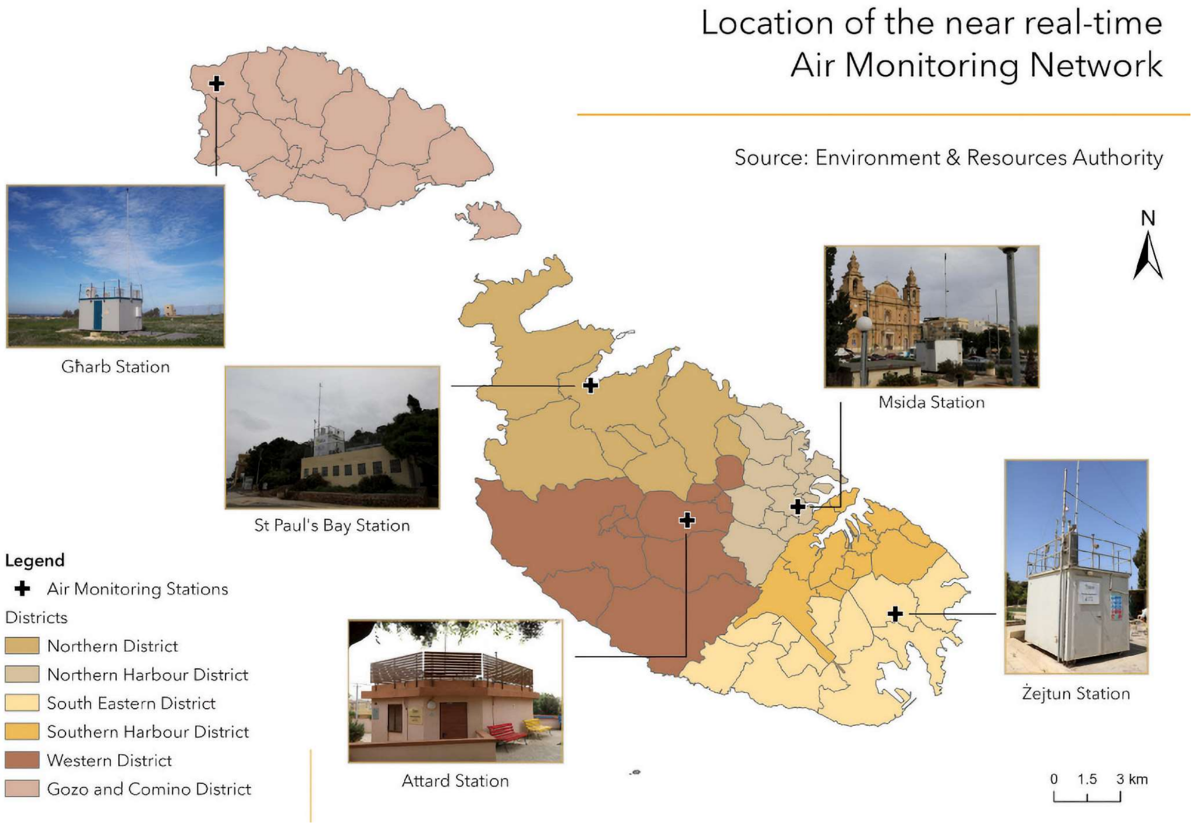
The stations in the real-time network are set in different locations in the country in order to capture different site characteristics (locations shown in Figure 3). The monitoring stations are situated in the following locations: two traffic sites in Msida and St. Paul's Bay, an urban background site in Żejtun, an urban site in Attard, and a rural background site in Għarb, Gozo (ERA, 2023).

According to the ERA (2019b), the primary source of air pollution in the urban regions is road transport. Elevated concentrations of particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide (CO) and nitrogen oxides (NO_X) are typically linked to areas with significant traffic congestion. Conversely, in rural areas distant from human-made emissions, the primary air quality issue revolves around elevated levels of ozone (O_3).

Table 1. Air quality monitoring station types & locations (ERA, 2023)

Type of Station	Locality
Traffic	Msida, Malta
Urban Background	Żejtun, Malta
Urban	Attard, Malta
Rural Background	Għarb, Gozo
Traffic	St. Paul's Bay, Malta

Figure 3. Locations of the near real-time air quality monitoring stations (ERA, 2023)



2.3. Traffic Limiting and Emission Reduction Measures

2.3.1. Contrasting Implementation Strategies

2.3.1.1 Push vs Pull Measures

Research on the topic of traffic emission mitigation strategies has introduced the distinction between measures that encourage and those that discourage a distinct mode of transport (Stradling et al, 2000). This distinction is often termed as the ‘push and pull’ approach, with a measure being either one or the other, or having the effect of both.

Push measures encompass a set of strategies designed to discourage the use of a transport mode, primarily private cars, as the primary mode of transportation within urban environments. These measures typically involve the implementation of charges, fees, and regulations that make private car usage less appealing or convenient (Kuss & Nicholas, 2022). For instance, congestion pricing, tolls, parking restrictions, and emissions-based regulations fall under the category of push measures. The application of these and other similar strategies is often rooted in the recognition of the negative effects associated with private car use, particularly air pollution.

On the other hand, pull measures refer to a distinct set of strategies aimed at enticing individuals to choose alternative modes of transportation over private cars. These measures can range from shorter journey times on public transport routes, educational campaigns, and cheaper public transport ticket prices (Dijk et al., 2018).

2.3.1.2 Scale and Area of Effect of Measures

Another distinction is the area of effect, where a vehicle emission reduction measure can either have a defined geographical location (a part of an urban area) or broader application area (nation-wide). (Stradling et al, 2000)

2.3.1.3 Public Opinion and Backlash

The increased prevelance in vehicle emission reduction measures in urban areas has led to significant public backlash, often due to perceptions of inconvenience, unfairness, or ineffectiveness. In London, the expansion of the Ultra Low Emission Zone (ULEZ) to cover all boroughs has sparked controversy. Residents on the outskirts, with less public transport access, feel disproportionately affected, leading to political tensions and promises of repeal by rival parties (Fisher & Austin, 2023). Similarly, New York City's proposed congestion charge has faced resistance from surrounding communities worried about increased commuting costs and local congestion (Ley, 2023). Studies suggest that acceptance of these measures depends more on political leanings, environmental awareness, and travel patterns than on socioeconomic factors like income and age (Tarriño-Ortiz et al., 2021).

2.3.2. International Case Studies

2.3.2.1 Price-Based Measures

Congestion charging and Low Emission Zone (LEZ) policies aim to reduce road traffic emissions within specific areas. Congestion charges apply fees to vehicles entering a zone during peak times to decrease traffic and emissions. LEZs restrict or fine vehicles that fail to meet emissions standards, aiming to improve air quality by limiting polluting vehicles' access to certain areas. These measures have been implemented in many major cities including London, Milan, and Rome, with their intended effect of reducing traffic and its associated emissions becoming well-documented successes (Beevers et al., 2016; Donggyun Ku et al., 2020).

2.3.2.2 Access Limitation Measures

Due to excessive volumes of traffic, congestion and harmful air quality diminish the quality of life of residents living in certain parts of the urban area. As a result, some city authorities apply access limitations to certain vehicle types or non-resident vehicles, usually taking effect during peak hours. Cities like Padova and Barcelona have become good examples after the success of their ‘Limited Traffic Zone’ and ‘Superblock’ policies respectively (Europe Interreg, 2019; POLIS Network, 2022).

2.3.2.3 Public Transport Improvements

Justifying the priority shift to public transportation in areas with high usage is straightforward. However, allocating the right level of priority becomes more complex in cities where public transport is less utilised (Currie et al., 2007).

Public transportation often appears less appealing than private cars due to its lack of flexibility and longer travel times, as it may not provide direct routes. The necessity of multiple stops for transfers also contributes to its perceived inefficiency compared to private vehicles, which share the same road space. In Toulouse, France, substantial upgrades to public transport have not only improved reliability, frequency, and punctuality but also positively shifted public perception, leading to increased usage and reduced congestion and emissions. (Institute for Transport Studies, 2021).

2.3.2.4 Carpooling

Carpooling, ridesharing, or car-sharing occurs when two or more travellers share a ride to a common destination, effectively raising the rate of vehicle occupancy, which is particularly useful during peak hours. Recent years have seen the growth of shared mobility options, particularly through app-based and on-demand transportation technology (Shaheen et al., 2018). The two forms of carpooling are casual carpooling, where a car is shared amongst friends or colleagues, and on-demand ride-shares, where strangers use the same vehicle using on-demand digital services (Szymanek et al., 2022). The implementation of carpooling measures rarely involves forcing people to participate and are usually concentrated in small areas, with most successful policies incentivising participation from educational institutions and workplaces (Parezanović & Pejčić, 2020).

2.3.3. Comparing Effectiveness of Different Measures

There have been several studies comparing and analysing the effectiveness of several traffic limiting and traffic emission reduction measures (Bigazzi & Rouleau, 2017; Haakman et al., 2020; Kuss & Nicholas, 2022).

Kuss and Nicholas (2022) found that congestion charging schemes were particularly effective, noting that London’s scheme had successfully reduced car use and associated traffic generated emissions. They also emphasized the success of Limited Traffic Zones in Rome and the positive effects of funding public transportation. Similarly, Bigazzi and Rouleau (2017) analysed multiple studies and concluded that the more restrictive strategies (access restrictions, low emission zones, and congestion pricing) show to be more effective, especially at combating emissions.

Supporting this, research by Ivanova et al. (2020) suggests that policies targeting the reduction of vehicle use in urban areas hold the greatest potential for reducing per capita emissions. The consensus across these studies is that the most effective measures are those that encourage a shift away from private vehicle use, aligning with broader environmental and air quality standards.

Furthermore, Fransen et al. (2023) cite the broad effectiveness of spatial interventions, particularly those that directly reduce private vehicle traffic and increase the usage of sustainable transport modes. Interventions like Barcelona's Superblock scheme and Ghent's traffic circulation plan being examples of such policies.

2.3.4. Maltese Context

2.3.4.1 Overview

This section documents some of the measures aimed at combating traffic generated emissions implemented and discussed in Malta. While these policies had already started being prioritised before the country’s accession to the EU[1], this effort clearly intensified due to enforced participation in EU emission reduction policies. Still, most of these measures do not discourage the use of private vehicles, rather encourage the shift to cleaner technologies (ERA, 2023).

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[1] *Malta joined the EU on 1st May, 2004 (European Commission, 2024b).*

2.3.4.2 Tackling Emissions at Source

An effective strategy at reducing road transport emissions is to mandate improvement in efficiencies of internal combustion engine vehicles (EEA, 2016). Since January 2003, leaded and unleaded petrol emitting benzene have been phased out, significantly reducing benzene concentrations (MEPA, 2006).

Another early measure was the introduction of the Vehicle Roadworthiness Test (VRT) in 1999, with the goal of enforcing minimum standards set for road vehicles. These tests usually check emissions, safety, and the vehicle's general condition. Over the years, stricter standards and spot-checks have been implemented (ERA, 2023).Economic measures, such as taxes on inappropriate fuels, have evolved to incentivise cleaner vehicles. Measures like the 'scrappage scheme' encourage replacing old vehicles with more efficient models, supported by grants for purchasing electric vehicles (EVs) (ERA, 2023).

2.3.4.3 Addressing Public Transport Issues

Moreso than other policies, improvement to public transport is a main policy that directly challenges the dominance of the private vehicle. In Malta's case, the primary public transport system is the bus service, which underwent a major overhaul in 2011 (Transport Malta, 2016). Consequently, a cleaner bus fleet, with Euro 5 and Euro 6 engines, contributed to significant pollutant reductions in areas like Msida and Żejtun[2] (ERA, 2023). Despite the continued addition of conventional diesel buses, Malta Public Transport (MPT) has started to introduce electric buses into its fleet, and it plans to bring on an additional 120 fully electric buses by the end of 2025 (Ellul, 2024).

Additional improvements include the Tallinja card system in 2015, which enhanced convenience and reduced boarding times (Malta Public Transport, 2021). Moreover, the bus service eventually become free as of October 2022. According to MPT (2023), modal share for buses has steadily increased to 11% in 2023. Still, there is debate about the long-term effectiveness of such public transport improvements in reducing car usage, without improving priority for the service with road network interventions (Transport Malta, 2016).

2.3.4.4 Active Mobility Plan

In 2023, the government launched a €35 million active mobility initiative to enhance urban transport options. This plan focuses on creating infrastructure that facilitates seamless transitions between various transport modes and improves access to public transport nodes. The project is currently in the early stages of planning and consultation (Ellul, 2023; ERA, 2023).

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[2] *Msida and Żejtun are localities with high bus concentrations (ERA,2023).*

2.3.4.5 Studying Low Emission Zones

Low Emission Zones (LEZ) are typically established in regions where vehicle-related air pollution poses a health risk to the public. Their purpose is to control the entry of highly polluting cars into certain locations. LEZs achieve this by either prohibiting the entry of these highly polluting vehicles or by charging them proportional to the amount they pollute (Transport Malta, 2016).

In 2007, the Controlled Vehicular Access (CVA)[3] system was introduced in Valletta, discouraging long term parking and unnecessary journeys. This led to a modal shift of about 10% away from private vehicles (Transport Malta, 2016).

In the Transport Master Plan 2025, Transport Malta (2016) outlines the need to study the implementation of LEZ policies, particularly in other dense, polluted areas of the country. Currently, there in an ongoing collaboration between the ERA and Transport Malta regarding the study of implementing an LEZ, with the long term aim being to induced travel behaviour change to improve air quality (ERA, 2023).

2.4. Traffic-Emission Air-Quality Modelling Process

2.4.1. Overview

An important step when implementing the traffic emission reduction strategies described in the above sections is to quantify their expected impacts on air quality. Existing studies have documented multiple methods of traffic-emission related air quality modelling (Forehead & Huynh, 2018; Mądziel, 2023; Perez-Prada & Monzon, 2017; Pinto et al., 2020)., with the more comprehensive strategies involving a three-step process:

- Traffic Modelling – To gather traffic data after modelling a road network change.
- Emissions Modelling – To quantify the amount of vehicle emissions exiting tail-pipes/exhausts of vehicles driving in specified conditions.
- Air Dispersion Modelling – To model how these tail-pipe/exhaust emissions spread after leaving the source.

In this section, a description of each part of the three-step process was given, with this information being used to establish the modelling methodology used and reported on in Chapter 3.

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[3] The CVA was introduced as part of the Sustainable Urban Mobility Plan (SUMP) for the capital city, Valletta (Transport Malta, 2016).

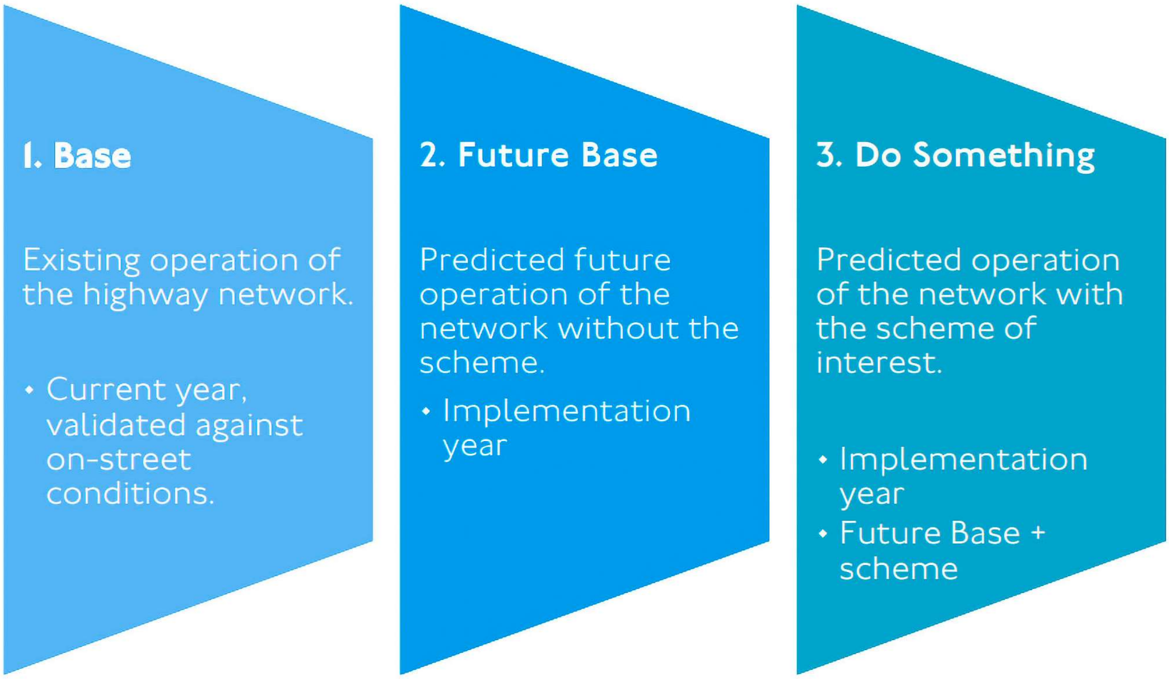
2.4.2. Microsimulation Traffic Modelling

Traffic modelling is considered an effective tool in the field of transport planning. Models can be used to simulate the change in behaviour of vehicles when applying changes to the modelled road network, making it useful for testing purposes. Depending on the scale and accuracy required for testing, traffic models are usually split into two main categories: macrosimulation and microsimulation (Krivda et al, 2021). While macrosimulation packages are used to get a general understanding of large model regions, microsimulation models offer greater levels of detail for smaller model areas (Raju & Farah, 2021). Specifically, microsimulation modelling permits the simulation of individual agents, including vehicles, cyclists, and pedestrians, with these agents following a set of behavioural rules calibrated in the model. These agents also follow a stochastic behaviour, so as to reproduce the dynamic and random behaviour of real-world events, leading to the higher levels of modelling accuracy required for certain scenarios, such as the scenario described above. This requires that several simulation runs are conducted in order to extract an average result (Transport for London, 2021).

The process of developing a microsimulation model involves several steps, these being outlined in further detail in Chapter 3. According to Transport for London (2021), the process involves three distinct stages (outlined in Figure 4). The first stage involves the creation of a base model that accurately represents the present conditions of the network in question. This starts with the selection of the study area and the defining of the area of influence, meaning finding out the extents of the real-world transport network needed to be modelled. The next step would be the identification and collection of input data (FHWA, 2019). The input data required includes network alignment, grades and geometry, local driving conditions and behaviours, vehicle fleet composition and traffic data gathered from on site (Quaassdorff et al., 2022; Raju & Farah, 2021). Following the insertion of this data into the model, the modellers could run the simulation. This would then involve reviewing the accuracy of the simulation against a representative period of the real-world network, also referred to as calibration. Calibration of the model involves the minimisation of differences between the simulation and real-world, with the quality of the microsimulation results being greatly reliable on this part of the process (Otković et al., 2020).

The second and third stages of the process involve running the simulation into the future, with the aim to see how future traffic volumes would impact the simulated model. The second stage usually involves the application of these future volumes on an unchanged network, in order to see what would happen in a ‘Do-Nothing’ scenario. The third stage would then involve the modelling of the envisaged network changes to see what would happen in a ‘Do-Something’ scenario. Therefore, the microsimulation traffic model would have outputted the results for both scenarios, enabling modellers and decision-makers to see how much the network changes affected the present network based on several key performance outputs. These outputs include journey times, average speed and traffic volumes.

Figure 4. The TfL three-staged traffic modelling process (TfL, 2021)



2.4.3. Emissions Modelling

Vehicle emission models estimate the level of exhaust emissions from the associated point sources (vehicles) based on various methods (Mądziel, 2023). Emission factors (EF) are the primary input data when calculating emissions, with these being coefficients that quantify the emissions for particular pollutants released per unit of activity (distance or time) (EEA, 2023). Consequently, their accurate collection is crucial, as the accuracy of emission models is limited by the quality of the EFs used in their calculations (Forehead & Huynh, 2018).

Hence, the formation of a reliable transport emission inventory specifically tailored to a country/region’s vehicle fleet is highly standardised and regulated (ERMES, 2021). The EMEP/EEA air pollutant emission inventory guidebook (EEA, 2023), outlines a three-tiered system for estimating emissions from sources, highlighting how road transport emissions typically use the most sophisticated Tier 3 methods, namely advanced models like COPERT™ (emisia, 2022) or facility-level testing.

Apart from EFs, emission models require other kinds of data, with different models being built to work at different levels of accuracy and data-resolution. (Quaassdorff et al., 2022; Smit et al., 2008).

Macroscopic emission models use low-resolution traffic and driving data, vehicle type proportions and averaged vehicle parameters, resulting in this model type being the furthest removed from traffic congestion effects. These models are adequate for the scope of creating emission inventories for national/regional vehicle fleets. Some examples of this software include COPERT™ and MOBILE™.

Microscopic emission models make use of high-resolution traffic data gathered either from the real-world or from microsimulation traffic models. These microscale models can be further categorized as static or dynamic emission models.

Static models factor in traffic congestion by considering parameters like average speed, vehicle proportion types, traffic volume and road network characteristics for individual road links. Examples include COPERT Street Level™ and MOVES™.

Dynamic emission models involve further integration with microsimulation traffic models, whereby data like vehicle speeds, acceleration/deceleration levels and idle time are inputted at the highest resolution (second by second). Passenger car and Heavy duty Emission Model (PHEM) is one such model (ITnA, 2024), with multiple microsimulation traffic models having their own dynamic modelling packages integrated into their software (e.g., AIMSUN™, Paramics Discovery™) (AIMSUN, 2024; SYSTRA, 2024).

2.4.4. Air Quality Modelling

Air quality modelling has developed to become an essential tool to assess the air quality and the level of emissions, especially after the EU-wide adoption of the AAQD of 2008. In fact, it has been emphasised that tools like real-time air quality monitoring and air quality models be used in conjunction to study the reach of air pollution from the source more accurately. There are several advantages to using air quality models, including the ability to be used in any location and the prediction of air quality into the future. However, for the purposes of this dissertation, air quality modelling is found to be of interest as it can be used for evaluating the effectiveness of measures that aim to reduce traffic-generated emissions before their implementation (EEA, 2011).

There are several types of air quality models, more specifically called dispersion models, that deal with simulating the concentration of different pollutants. These models vary in capabilities as they would be built to simulate emissions from different sources, like point, line or area sources, and different pollutant types (EPA, 2023).

In the case of this research, consideration was given to dispersion models that can simulate pollutant dispersion from roadway (line) sources. Most of these dispersion modelling tools use Gaussian formulation to describe the movement of air due to atmospheric processes, which is involved in the dispersal of emitted pollutants from sources, including vehicle emissions (Pinto et al., 2020). By using emissions and meteorological data, dispersion models predict concentrations within an area around the emission source (EPA, 2023). Some of the main dispersion modelling solutions include the CALINE series, AERMOD and R-Line. When choosing a model, one must also consider the site and situation being modelled, with consideration being given to topography, degree of urbanisation and height of buildings along the street (Heist et al., 2013).

2.5. Research Gap

As referenced in section 2.3.4.5, the Transport Master Plan 2025 (Transport Malta, 2016) states the need to test policies to improve urban air quality in Malta. As of the writing of this dissertation, there is no indication of a plan of how this can be achieved. Section 2.4 outlines a process documented in the literature by which the goals of the Transport Master Plan 2025 can be achieved. This dissertation will address this local research gap, as demonstrated in the following chapters.

2.6. Summary

This chapter involved the exploration of different concepts pertaining to the issue traffic-generated air quality issues.

Section 2.2 gives context on how vehicle emissions are formed, and the laws and regulations aimed to mitigate them. This helped to justify the importance of the research topic in question, especially considering how the Maltese vehicle fleet lags behind in terms of fleet average age.

In Section 2.3, different methods at combating subpar air quality were documented, with both international and Maltese strategies explored. This provided useful insight when selecting the area of the Maltese road network, and traffic-emission reduction strategies that were studied (this process being outlined in further detail the upcoming chapter).

Section 2.4 describes a three-stepped approach by which these strategies can be digitally tested before their implementation in the real-world. Through this approach, which was tested by a number of previous international studies, a methodology for each step was developed on how this can be applied within the Maltese context (further outlined in Chapter 3).

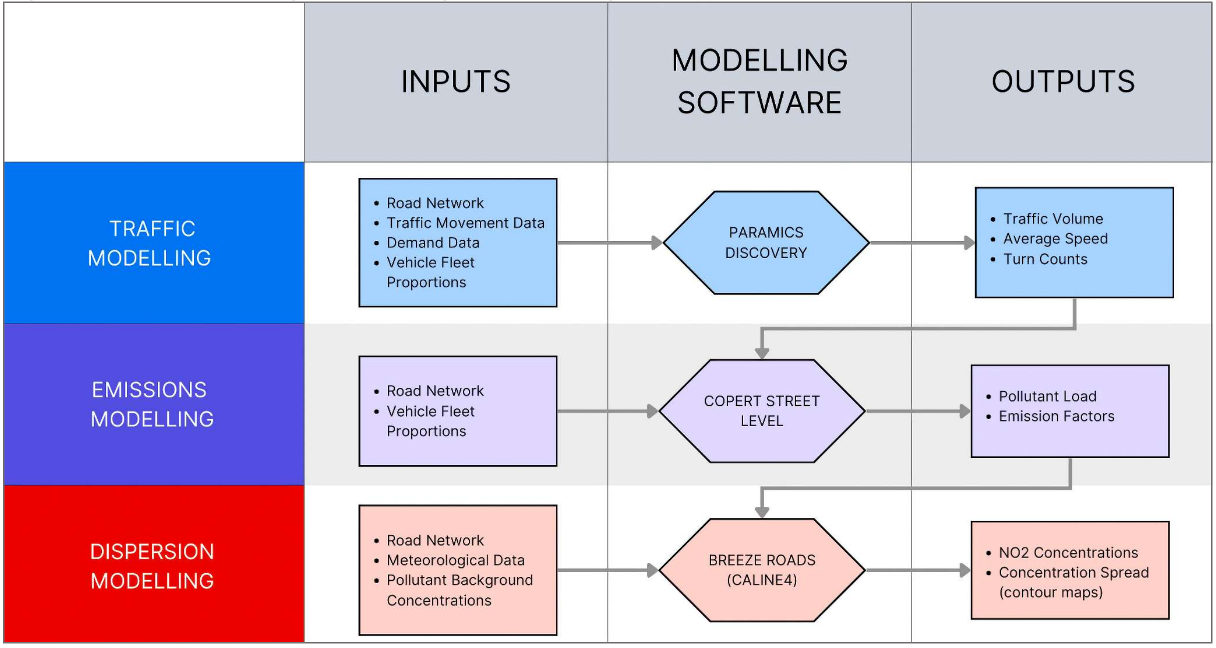
CHAPTER 3 - METHODOLOGY

3.1. Overview

This study intends to find out how a change in the behaviour of traffic affects air quality in a particular area. This required the comparison of the current, present-day scenario with the proposed experimental scenarios, for both traffic and air quality metrics. It is important to note that, for this study, nitrogen dioxide (NO_2) was selected as the primary pollutant for analysis. NO_2 is widely recognised as a significant contributor to health problems associated with traffic emissions (EEA, 2016).

This section outlines the three-step process (summarised in Figure 5) for how this was achieved, particularly what each part of the process required in terms of inputs, the modelling software used, and the outputs produced This chapter also includes details on the specific software and data used during each step.

Figure 5. A workflow diagram showing the modelling process followed



3.2. Study Area Selection

3.2.1. Overview

The first part of this research involved the identification of an area in Malta, in which a potential traffic limiting measure could be introduced, and about which traffic, emission, and other data are available. The definition of several criteria for selection endeavoured to improve the likelihood of choosing a study area with the potential to enable the production of viable results, within a framework characterised by limitations connected with time, finances, and human resources. The following section defines the considered criteria for selection, these being:

- Size
- Emissions
- Complexity
- Data Availability

3.2.2. Ideal Study Area Criteria

3.2.2.1 Size

The size of the potential study area was considered from the start of the selection process. It was also considered important for the study to model a cohesive network, rather than individual links and junctions, as this would provide a level of realism required for the making of viable predictions regarding proposed scenarios. Choosing an optimal size of the network allows the traffic simulation to react appropriately, by, for example, allowing simulated vehicle agents to reroute onto alternative parts of the modelled network, when the need arises.

3.2.2.2 Emissions

The concentration levels of pollutants in candidate areas were an important consideration given the aim of the study was the analysis of traffic-limiting measures designed to reduce emissions. The pollution levels of the area had to be close or exceeding limits, with the study focusing on NO_2 concentrations. Therefore, by using data provided by the ERA (2024a), different considered sites were scrutinised based on if NO_2 concentration levels approached or exceeded the limit of $40\mu g/m^3$ set by the AAQD, this having been discussed in section 2.2.1 (p.g.5). At the time of the study, the most recent pollution data was gathered from the ERA. This set of data was collected through the passive diffusion tube network and the real-time air quality network, mentioned in section 2.2.3 (p.g.8).

The selection was also influenced by whether or not the primary emission source in an area is related to vehicle emissions. Multiple emission sources were expected to influence emissions reduction measures, so it was considered advantageous for the study area to have emission levels primarily influenced by road transport.

3.2.2.3 Complexity

Complexity refers to the density of the road network. This density was determined by indicators such as the proximity of intersections/junctions, length of road network, the number of traffic generating centres of activity and connectivity, and/or the connections between such centres within the study area.

Generally, different areas of a road network have varying densities, with the Maltese road network being no exception. However, given that Malta is the most densely populated country in Europe (European Commission, 2023a) ,most of the road network can be considered dense, this being made particularly evident by extensive urban sprawl. The complexity of the road network is at its worst where you have different villages developing close to each other. Ideally, an area like this would be avoided, but this development morphology is very common throughout the Maltese urban area (Zammit, 2022).

3.2.2.4 Availability of Traffic Data

In order to conduct an accurate traffic simulation, information from different data sources need to be acquired, including vehicle counts, types of vehicles, directional turn counts and traffic-light timings. In practice, if funds are available, this may not be a limitation, as any selected part of the road network can be studied to gather this information.

3.2.3. Considered Study Areas

The selection process started with the identification of areas which appeared to be seriously affected by NO_2 pollution in the ERA's 2023 data. The candidate areas were further studied and judged with reference to the complexity of their road network.

The extents of the road network were determined by considering whether vehicles would have alternative routes after an intervention was proposed. Moreover, the sites were studied based on what type of interventions that could be modelled.

After determining the general extents of the study area required to effectively model a road network change, the size of this associated road network was considered. Only areas that were seen to be manageable were considered, given the mentioned limitations. Finally, the shortlisted areas had to have sufficient data available in order to speed up the modelling process. Therefore, the relevant transport authorities were contacted to find out what areas had the most recent and best coverage of data for most of the modelled road network.

Table 2. Considered Study Areas

Considered Areas	Size	Emissions	Complexity	Data
Central Business District (CBD)	✓	✓✓✓	✓✓	✓✓✓
Triq Misraħ Kola, Attard	✓✓✓	✓✓	✓	✓✓
Triq Ġebel San Martin, Żejtun	✓✓	✓✓✓	✓	✓
Triq Sant' Anna, Floriana	✓✓✓	✓	✓	✓✓✓
Paceville, St. Julians	✓✓	✓✓✓	✓	✓✓✓
Ħal Għaxaq	✓✓	✓✓✓	✓✓✓	✓✓

Note: ✓=Low Suitability, ✓✓= Medium Suitability, ✓✓✓=High Suitability

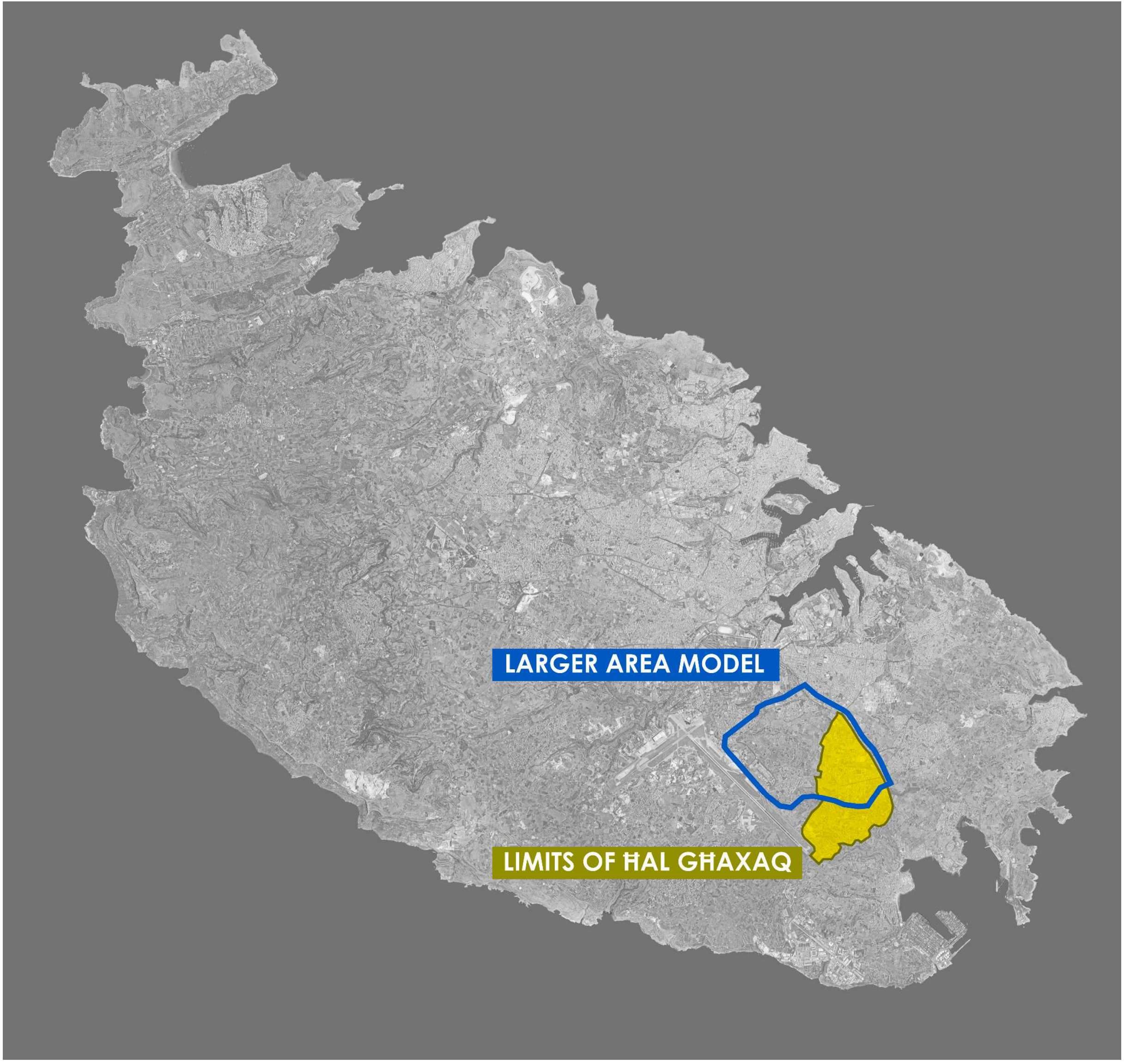
3.2.4. Selected Study Area

By following the process explained in the previous section, the candidate areas were evaluated and narrowed down to the final choice, this being the locality of Ħal Għaxaq.

Firstly, the ERA's NO_2 concentration data indicates that an air quality receptor next to Dawret Ħal Għaxaq had a concentration level of 44.4µg/m^3 in 2019 (before the COVID-19 pandemic) and 38.5µg/m^3 in 2023 (after the pandemic). These emission levels are characterised as traffic-related emissions, meaning vehicle emissions are the primary source. At these levels, it was conjectured that an effective vehicle emission reduction measure, through traffic limitation measures, had the potential to be applied.

Secondly, the development pattern of Ħal Għaxaq offers an interesting and representative case study into urban sprawl and the merging of different urban morphologies. Therefore, the method applied in this study area could be replicated in other parts of the urban region, possibly on a larger scale. Another point of interest is that Dawret Ħal Għaxaq road was constructed as a bypass for vehicles to circumvent the village core. However, as a result of poor development control, further urban development was allowed to take place on the south side of this bypass throughout the end of the 20th century, with this still continuing to this day. In fact, presently, a sizeable part of Ħal Għaxaq's population is segregated from the village core by the bypass, which nowadays services increasingly high traffic volumes. This resulted in a disconnected community, increased hazards for pedestrians and, pertinent to this research, increased emission levels in the centre of the locality.

Figure 6. The local council boundary of Ħal Għaxaq & the road network being modelled



3.3. Preferred Traffic Limiting Measures

3.3.1. Overview

As discussed in section 2.3.1 (p.g.10), there are differing approaches when introducing a measure aimed at combating traffic and its associated emissions, especially when it comes to the differences between push and pull measures, and the scale of implementation. Moreover, in sections 2.3.2 (p.g.11) and 2.3.3 (p.g.12), different measures were documented to have worked in different international contexts, with varying degrees of success.

With the issue of policy transfer (discussed in section 1.2, p.g.3) kept in mind, this section discusses the types of measures considered for testing in this study.

3.3.2. Defining Measures and Expected Results

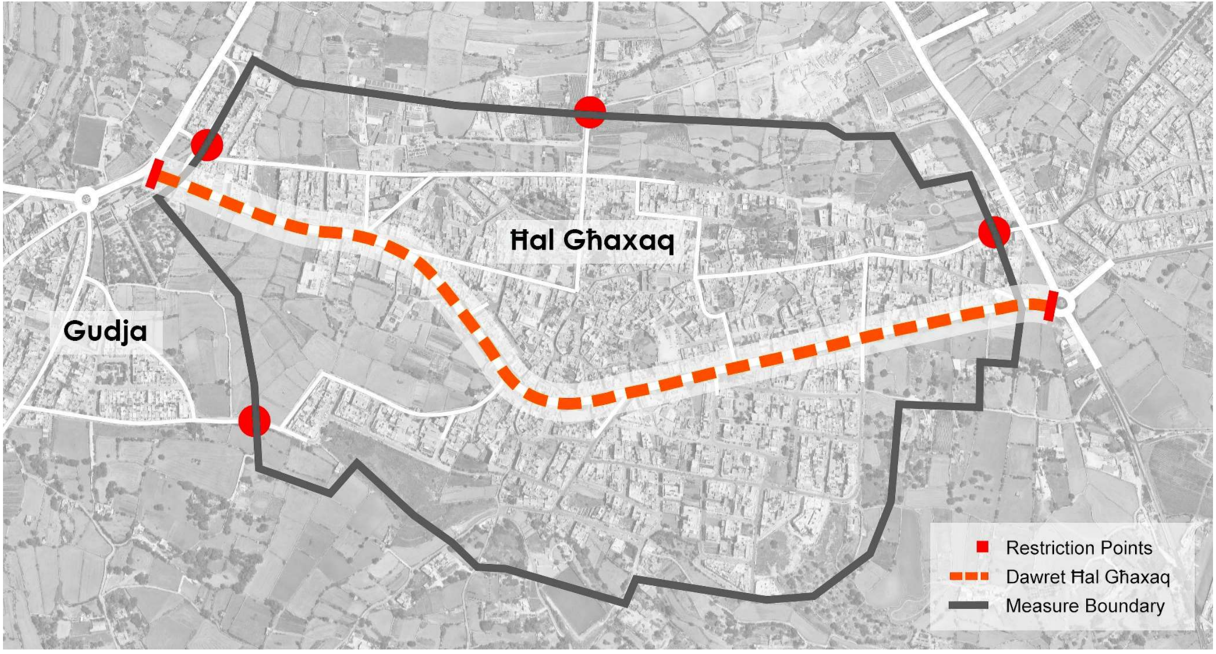
3.3.2.1 Measure 1 – Access Restriction

It was decided that a push measure, meaning a measure that discourages the use of private vehicles, should be tested. This approach contrasts with the typical direction of transport policies in Malta, where decision makers often opt for using incentives (pull measures) to exact change in the behaviour of transport users.

Another consideration was the scale of application of these measures, whether through national policy or local network changes. In order to showcase the capabilities of a microsimulation traffic network model, it was decided that a proposed local network change should be tested. The selection of Ħal Għaxaq as the study area provided the opportunity to apply a network change in the form of a traffic limiting measure, primarily involving the restriction of through-traffic within the locality's urban area. Effectively, this measure would convert Dawret Ħal Għaxaq road, which bisects the locality's urban area, into a local road. To practically implement this measure in the real-world, ANPR cameras can be used to monitor the access points at the measure boundary (refer to Figure 7).

In other words, this measure differentiates between vehicles registered to residents or businesses in Ħal Għaxaq and those that are not, permitting only the vehicles registered in Ħal Għaxaq to pass. In the form this measure was tested, zero-emission vehicles were not exempt from this restriction. As a result of this road network change, it was hypothesised that traffic flows would decrease on Dawret Ħal Għaxaq road, with a similar decrease expected for traffic generated emissions. The study of this specific strategy aims to check the validity of this hypothesis and to see whether it would produce negative results on other parts of the road network.

Figure 7. Map of the boundary of Measure 1 within Ħal Għaxaq



3.3.2.2 Measure 2 – Carpooling

The process of traffic and air quality modelling can also be used to test the impact of larger-scale policies on a part of the road network. Hence it was decided that a measure for carpooling would be studied.

The method for modelling this measure involved the manipulation of the origin-destination demand matrix (process further described in section 3.4.6.2, p.g.30), with the road network not being modified. Two options were considered when deciding the scale of the measure;

- Global Application – every trip in the demand matrix affected by measure.
- Targeted Application – targeted trips in the demand matrix affected by measure.

The targeted application of the carpooling policy was considered the more realistic, yet conservative approach. Specifically, the application of this policy was targeted towards trips that involved popular work and education based destinations, including Msida, Mrieħel, Valletta, and Floriana[4]. The application of this carpooling measure for trips involving these specific destinations was considered given how, apart from reducing single-occupant vehicle trips, it can be effective at reducing strain on parking facilities at these places.

The practical application of this measure in the real-world would most effectively been done through incentives, such as preferential parking closer to the destination and exemptions from parking fees. It was hypothesised that the simulation of this measure would result in an overall reduction in traffic congestion, with this being coupled by a reduction in traffic generated emission.

3.4. Microsimulation Traffic Modelling

3.4.1. Overview

As described in section 2.4 (p.g.14), the first part of the traffic-emission modelling approach is the development of a traffic microsimulation model. This section describes the overall approach adopted when constructing this digital model for the selected area. In general, guidance for the modelling process was taken from the UK's 'Transport Analysis Guidance' (Department for Transport, 2020). During this study, Paramics Discovery™ v26.0.3 was used as the modelling software. The latest manual (SYSTRA, 2022a) for this software was also consulted for guidance during the modelling process, along with some case studies which refer to the use of this package (SYSTRA, 2018, 2022b).

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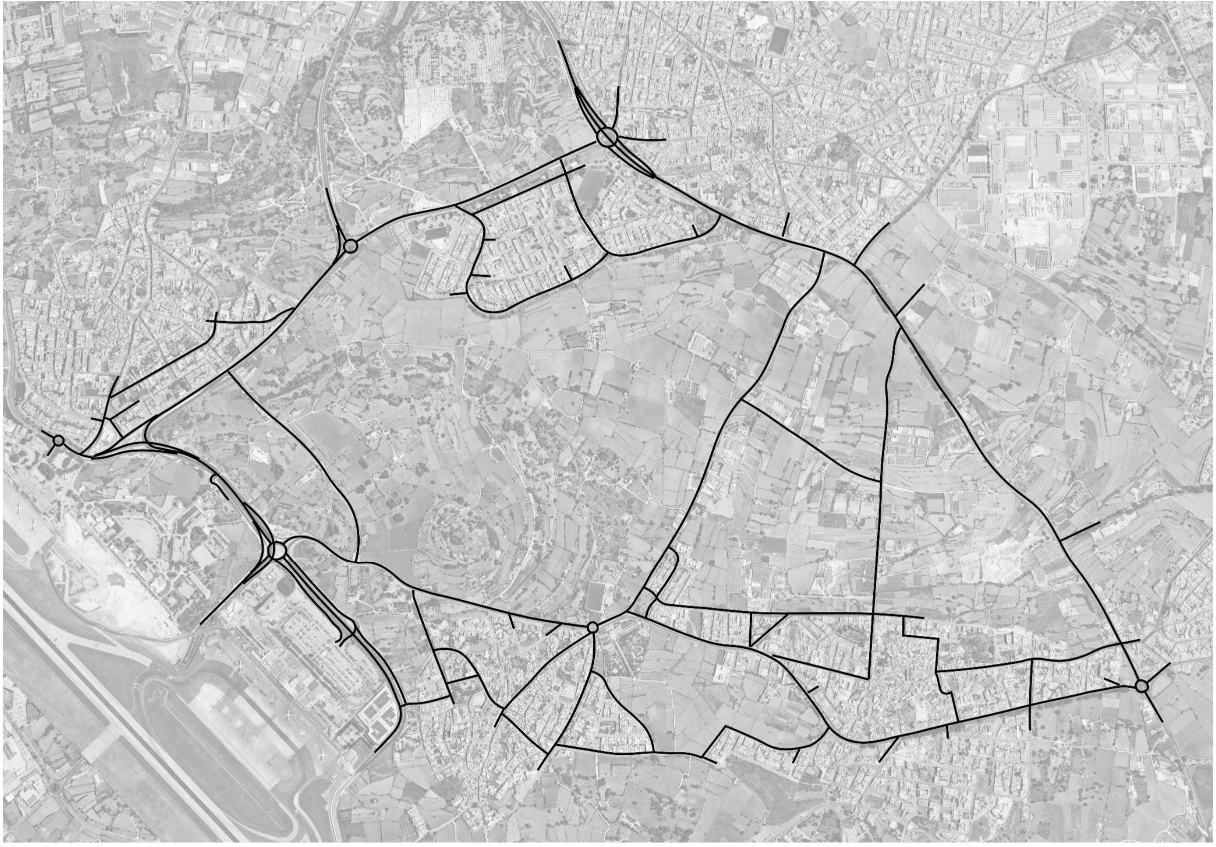
[4] *Localities and zones that are major nodes for employment and educational trips in Malta (NSO,2022).*

3.4.2. Defining and Modelling Road Network

As previously stated, the study area revolved around the locality of Ħal Għaxaq, particularly Dawret Ħal Għaxaq road. In order to appropriately study the impact of the applied road network changes, a model covering a larger area was deemed necessary (defined in Figure 8). This aided in identifying any alternate routes taken by vehicles due to the proposed changes. It was decided that with this larger area, several major junctions needed to be included as well. After deciding what part of the road network was to be modelled, survey plans of the road network were collected from the relevant authorities so an accurate layout of the links and junctions could be achieved. The modelling of the road network within the traffic modelling software is outlined in Appendix A.1.

Figure 8. Map of the selected road network to be modelled



3.4.3. Traffic Data Gathering

3.4.3.1 Existing Data

The development of a microsimulation model involves the collection and organisation of traffic data including turn counts, queue lengths, and journey times for specific routes. Ideally, the current day traffic flows would be accurately documented with automatic traffic counts and/or registration number surveys (National Highways, 1996).

In the case of this research, existing data from different sources was collected at different points on the network (shown in Figure 9 and Table 3). Some of this data was the latest data available, namely link and turn count data from the traffic-light junctions on Tal-Barrani Road (labelled as Signalised Junctions). Other data from past year was collected, meaning an adjustment of this data was necessary to reflect changes in traffic volume.

This was achieved by using the daily traffic counts data gathered by the traffic-light junctions to establish growth rates that can be used to extrapolate older data to the latest date. Moreover, for the purposes of this study, only the morning peak hour, between 7am and 8am, of a typical working day was considered.

3.4.3.2 Manually Gathered Data

While existing data covered most of the crucial locations of the study area, there were some particular spots on the network where data was not available. This resulted in the need to manually collect certain datasets considered crucial for the modelling process (labelled as Manual Counts in Figure 9).

Figure 9. Locations of traffic data gathered within the study area network

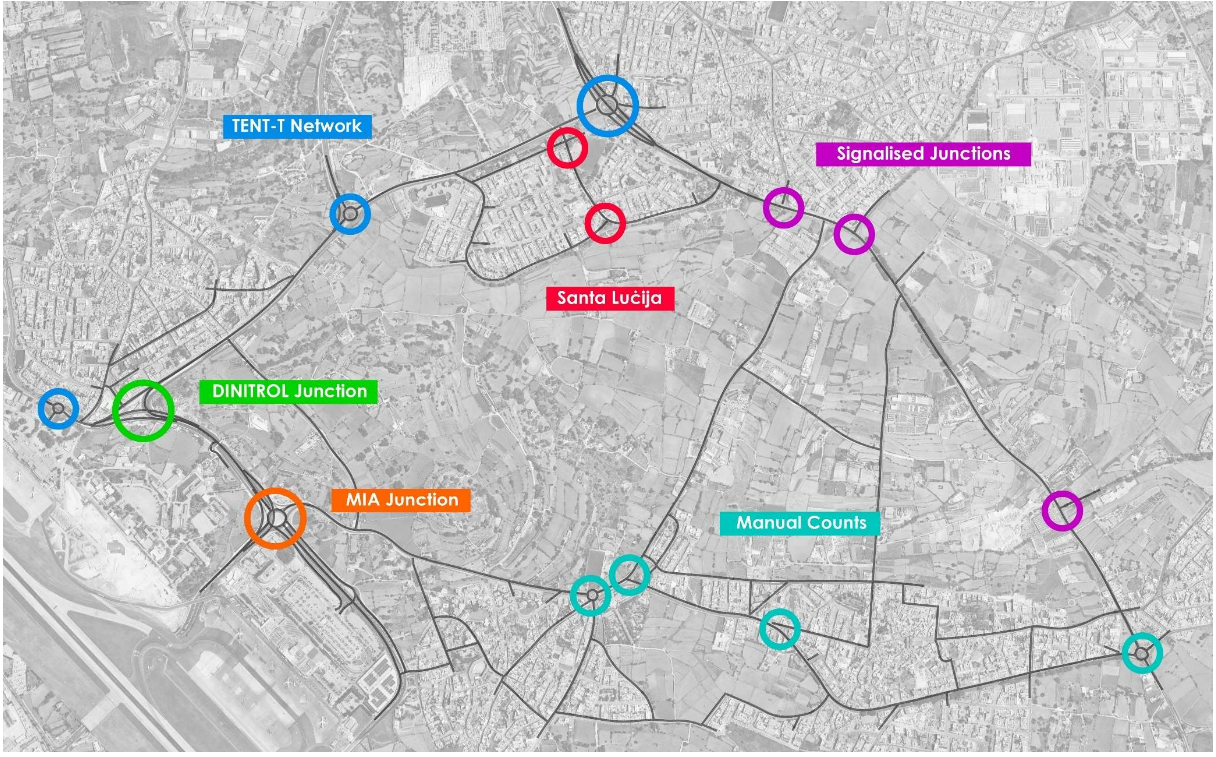


Table 3. Identifying data gathered from junctions of the study area network

Identifier	Data Type	Year	Source
🟥 Santa Luċija	Turn Counts	2022	Traffic Impact Assessment (PA6394/21)
🟦 TEN-T Network	Turn Counts, AADT/Flow values	2021	Infrastructure Malta (IM)
🟩 DINITROL Junction	Turn Counts, AADT/Flow values	2018	Infrastructure Malta (IM)
🟧 MIA Junction	Turn Counts, AADT/Flow values	2018	Infrastructure Malta (IM)
🟦 Manual Counts	Turn Counts	2023	Manual Counts (collected by author)
🟪 Signalised Junctions	Turn Counts	2023	Transport Malta (TM)

3.4.4. Demand Matrix Development

3.4.4.1 Overview

Paramics Discovery™ makes use of origin-destination (O-D) demand matrices in order to control the release and intake of vehicles from and into specified zones. A distinction must be made between traffic demand (the number of vehicles aiming to pass through the modelled network) and traffic counts (the number of vehicles recorded to have passed through the modelled network) (SYSTRA, 2022a).

An O-D matrix governing the traffic simulation is formed using the 'Estimator' tool within the programme, where the matrix estimation process takes place. The process started with first defining a preliminary pattern/prior matrix that would serve as a benchmark for developing a more accurate traffic demand matrix (further described in Appendix A.2). This was followed by inputting traffic data in the form of recorded, real-world traffic counts. Paramics Discovery™ then takes the initial pattern/prior matrix and outputs modified O-D matrices which consider traffic counts data, with each iteration getting closer to the real-world situation (Roads & Traffic Authority, 2009).

3.4.4.2 Matrix Estimation

After development of the prior matrix, the Paramics Discovery™ model was given this initial demand matrix to generate routeing data in the form of PIJA files[5]. This set of routing data roughly matches up trips identified in the prior matrix to each link and turn in the model, with the simulation making use of this in the subsequent matrix estimation process (SYSTRA, 2018).

The matrix estimation process mainly used three data sets – observed survey data, the prior matrix, and the PIJA routing data – and was specified to carry out five iterations, with the output being a new demand matrix. The newly generated demand matrix was then applied to the model, followed by a process of calibration to check the accuracy of the simulation against the real-world traffic situation. The results from the calibration process would inform further refinement of the prior matrix and updating of the PIJA routing files.

3.4.5. Calibration and Validation

3.4.5.1 Overview

Microsimulation traffic modelling software, like Paramics Discovery™, make use of the stochastic traffic flow model. This is a method of mathematically representing the randomness exhibited by flowing traffic, governed by empirical data on vehicle dynamics (Storm, 2021). Still, variations are always found between the model and the real-world traffic conditions.

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[5] *PIJA files are a specific file format to store and manage input data for the simulation within Paramics Discovery*

Therefore, modelling software like Paramics Discovery™, employ a system of calibration and validation to aid the modeller in gauging accuracy of the simulated model.

3.4.5.2 Calibration

First step in this process involves checking that the real-world data was properly inputted into the software, particularly link and turn counts. Once this is confirmed, a comparison between modelled results and the observed data needs to take place. One tool used in traffic modelling is the GEH statistic, this being used to check for differences between real-world and simulated traffic flows on different links within the model (Transport for London, 2021).

Several guidelines on this topic (Department for Transport, 2020; National Highways, 1996) suggest that, to maintain a certain level of accuracy, 85% of individual flows in the model should have a GEH of less than 5. In this case, out of the 78 specified movement counts, 85.33% achieved a GEH value below the set maximum GEH value of 5, meaning the model accuracy can be considered satisfactory from this aspect.

3.4.5.3 Validation

Comparison of several modelled journey times against observed (real-world) journey times was conducted as the main method of data validation. According to traffic modelling guidelines, modelled journey times should not have a difference greater than 15% from real-world observations. Table 4 and Figure 10 show the several routes considered across the modelled network along with a comparison of journey times.

Figure 10. Map showing journey time routes

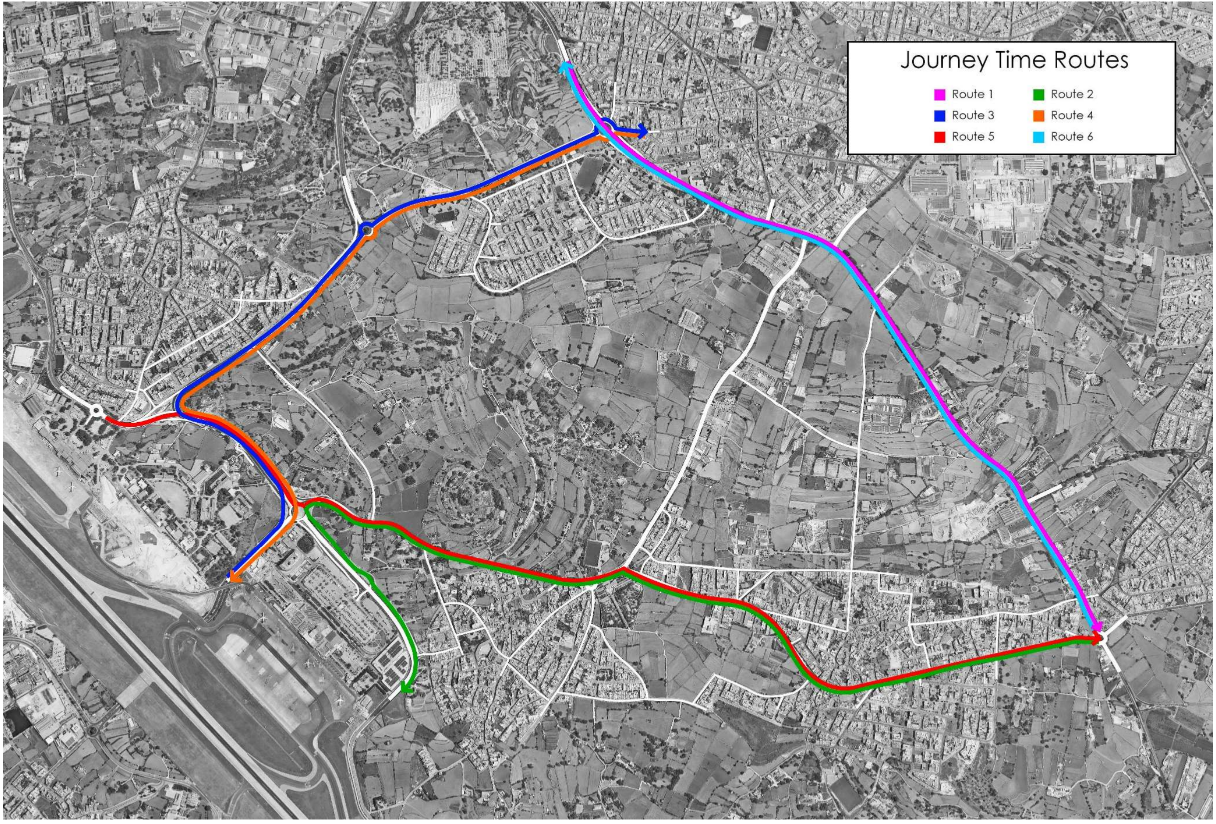


Table 4. Comparing observed & modelled journey times on several routes

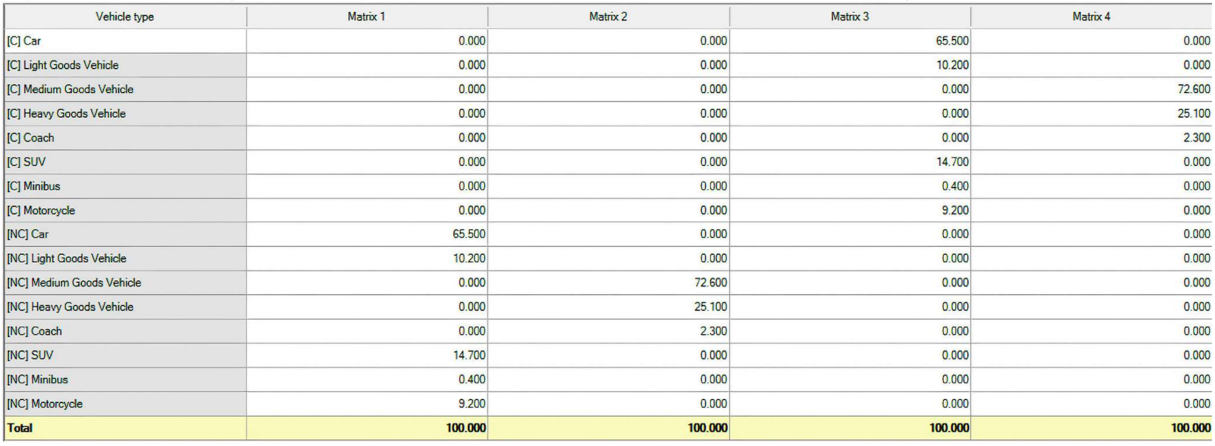
Routes	Observed Time (s)	Model Time (s)	Percentage Difference
Route 1	586.0	651.0	11%
Route 2	446.0	464.5	4%
Route 3	387.0	361.7	7%
Route 4	256.0	284.2	10%
Route 5	586.0	675.2	14%
Route 6	512.0	566.3	10%

3.4.6. Modelling the Proposed Measures in the Traffic Model

3.4.6.1 Measure 1: Access Restriction

The categorisation of vehicle types was done to simulate the traffic limiting measure being modelled (described in section 3.3.2.1, p.g.24). A distinction between vehicles associated with Ħal Għaxaq (labelled [C] for Compliant) and those not associated with Ħal Għaxaq (labelled [NC] for Non-Compliant) was made in order to achieve this. Figure 11 shows how vehicle types were split between [C] and [NC] within the software.

Figure 11. Vehicle types and proportions as shown within Paramics Discovery



Vehicle type	Matrix 1	Matrix 2	Matrix 3	Matrix 4
[C] Car	0.000	0.000	65.500	0.000
[C] Light Goods Vehicle	0.000	0.000	10.200	0.000
[C] Medium Goods Vehicle	0.000	0.000	0.000	72.600
[C] Heavy Goods Vehicle	0.000	0.000	0.000	25.100
[C] Coach	0.000	0.000	0.000	2.300
[C] SUV	0.000	0.000	14.700	0.000
[C] Minibus	0.000	0.000	0.400	0.000
[C] Motorcycle	0.000	0.000	9.200	0.000
[NC] Car	65.500	0.000	0.000	0.000
[NC] Light Goods Vehicle	10.200	0.000	0.000	0.000
[NC] Medium Goods Vehicle	0.000	72.600	0.000	0.000
[NC] Heavy Goods Vehicle	0.000	25.100	0.000	0.000
[NC] Coach	0.000	2.300	0.000	0.000
[NC] SUV	14.700	0.000	0.000	0.000
[NC] Minibus	0.400	0.000	0.000	0.000
[NC] Motorcycle	9.200	0.000	0.000	0.000
Total	**100.000**	**100.000**	**100.000**	**100.000**

3.4.6.2 Measure 2: Carpooling

The effect of this measure was quantified by finding out how many vehicles within the model were going to those four places (which boundaries were informed by the National Transport Model TAZs). This value amounted to about 1,200 vehicles, which represented around 10% of the modelled vehicles. Then, it was assumed that, conservatively, there would be a 50% reduction in this amount, which equates to around 600 vehicles that now have multiple occupants. This reduction was then distributed amongst the traffic model exit zones that were responsible for taking in vehicles going to the targeted carpooling areas (refer to Table 5).

Table 5. Difference in values used in demand matrices, before & after Measure 2

Exit Zones	**Matrix 1** **Ħal Għaxaq** **Compliant LVs**		**Matrix 2** **Ħal Għaxaq** **Non-Compliant LVs**	
	Before Matrix 1	After Matrix 1	Before Matrix 3	After Matrix 3
7	2550.8	2227.2	183.0	144.1
30	1068.5	927.7	65.2	48.2
33	722.6	528.8	41.6	18.3

Note: LVs (light-vehicles) – Passenger Cars, Light Goods Vehicles, Motorcycles

3.4.7. Processing Generated Outputs

The traffic model generated traffic volume values for each link in the network, using data collected during the peak morning hour from 7am to 8am. However, the data gathered from the ERA's passive diffusion tube network provided monthly average pollutant concentrations. This meant that the pollutant concentration data had a lower time resolution compared to the traffic modelling data.

Since the peak hour traffic volume is not representative of the average monthly volume, there needed to be an extrapolation of the peak hour traffic data to a monthly average. To do this, hourly traffic volume data (collected from the signalised junctions) was used to establish a relationship between the peak hour traffic volume (7am to 8am) and the average monthly hourly volume.

After analysing data from October 2023, the average hourly volume in a month was found to be 71.39% of the traffic volume recorded between 7am and 8am. This relationship (established through the signalised junctions data) was then applied to the volumes generated from the model across the entire network, assuming that the relationship observed at the signalised junctions is representative of the entire network. These adjusted volume values were then used in subsequent parts of the process.

3.5. Emission Modelling

3.5.1. Overview

Apart from data describing the behaviour of traffic on the road network, dispersion modelling requires information concerning emissions produced by said traffic. This section describes how this emissions data was gathered, quantified, and formulated accordingly, using emission modelling software COPERT Street Level™ (EMISIA SA, 2024b).

3.5.2. Emission Factors

Emission factors (EF) are values (represented in g/veh-km) used to represent emissions for pollutants coming from vehicle exhaust at a certain speed, quantified by the amount of pollutant released to the atmosphere relative to the activity associated with its release. These factors are usually specified to a country or region's vehicle fleet and are influenced by characteristics like average age of vehicle fleet, average speed and fleet composition (Forehead & Huynh, 2018).

Currently, the Computer Programme to calculate Emissions from Road Transport (COPERT) (EMISIA SA, 2024a) and the Handbook on Emission Factors for Road Transport (HBEFA) (INFRAS, 2024) are the two predominant macroscopic emission models in Europe (Tsanakas, 2019). These resources provide a standardised database for most national vehicle fleets in the EU, yet Malta's default fleet data is not well represented.

Malta's Annual Informative Inventory Report (ERA, 2024b) provides a solution to this issue, whereby accurate national fleet data was used to inform more localised emission factors. Particularly, the ERA made use of Tier 3 emission modelling methodology (referenced in section 2.4.3, p.g.16) in the form of the vehicle emission model COPERT™ Version 5.7.2.

Local vehicle registration data was used to quantify the amount of stock for each vehicle category according to the COPERT™ standard categories. Moreover, modelled activity data, obtained from the National Transport Model (NTM) (ERA, 2024b) was collected to find the mean activity for each vehicle category.

While these EFs are more accurate than using ones from other national fleets, they are formed from an averaging of conditions across the entire Maltese road network. This means that these EFs are not fully representative of the conditions of the road network being studied around Ħal Għaxaq.

Therefore, it was decided that, by using the same vehicle fleet proportions used by the ERA, while substituting mean activity data with activity data from the traffic model for each link, EFs that are more tied to the conditions of the study can be found. Specifically, COPERT Street Level™ was used, this software having the capacity to calculate EFs for each road link modelled (Forehead & Huynh, 2018). It should be noted that COPERT Street Level™ only estimates hot exhaust emissions (Liora et al., 2021).

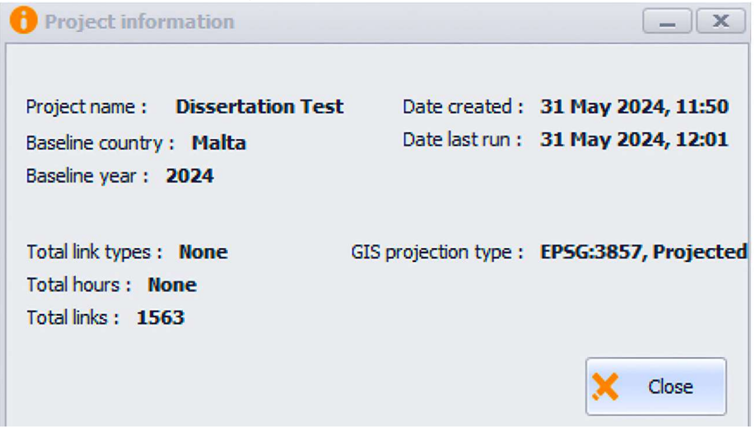
3.5.3. Emission Modelling Process

The process started with characterising the vehicle fleet, identifying the country of origin and the baseline year (refer to Figure 12). However, given how the software uses international databases, the proportions for the Malta fleet, attributed to the chosen baseline country, were not accurate. Therefore, the proportions for each vehicle category were inputted manually.

These include vehicle sector (refer to Figure 14) (passenger car, light commercial vehicle, heavy duty trucks, buses, mopeds, and motorcycles), fuel type (Figure 16), (leaded and unleaded petrol, diesel, LPG, hybrid gasoline, CNG, and bioethanol), and engine technology (Figure 15) (according to emission standards) (Sánchez et al., 2021).

It then required data on the road network, including the length and coordinates of each road link (refer to Figure 13). Crucially, the model needed inputs like average speed and traffic volume for each road link, sourced from the microsimulation traffic model. This data allows COPERT Street Level™ to calculate emission factors accurately based on specific traffic conditions.

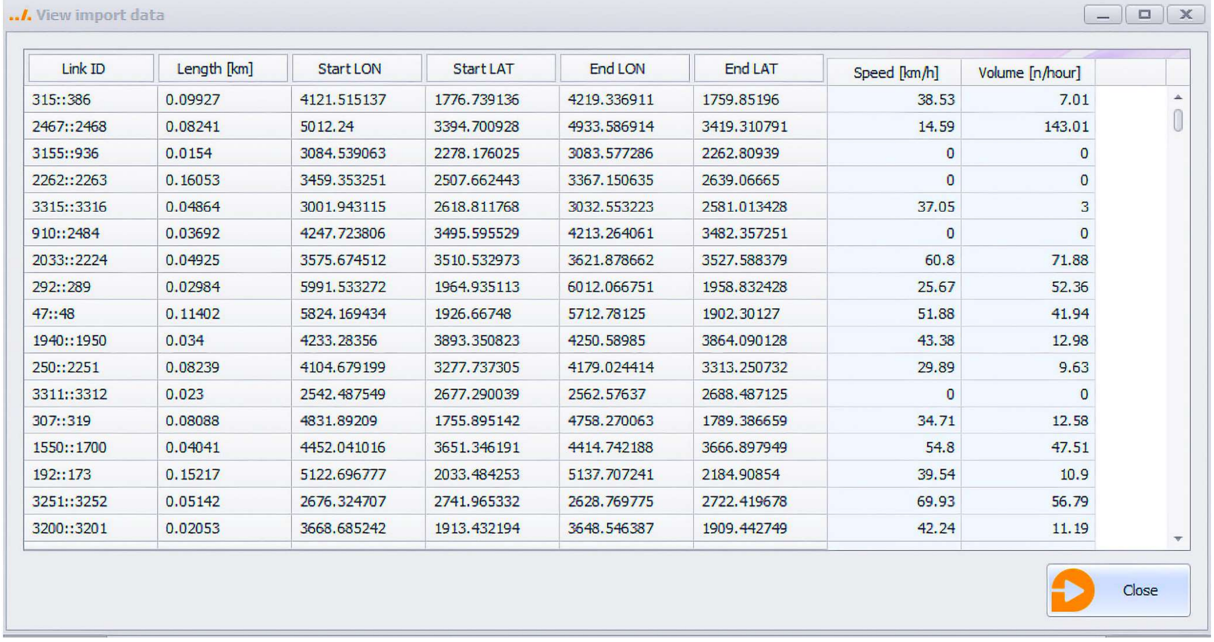
Figure 12. Project information required by COPERT Street Level



Project name : **Dissertation Test**
Baseline country : **Malta**
Baseline year : **2024**
Date created : **31 May 2024, 11:50**
Date last run : **31 May 2024, 12:01**

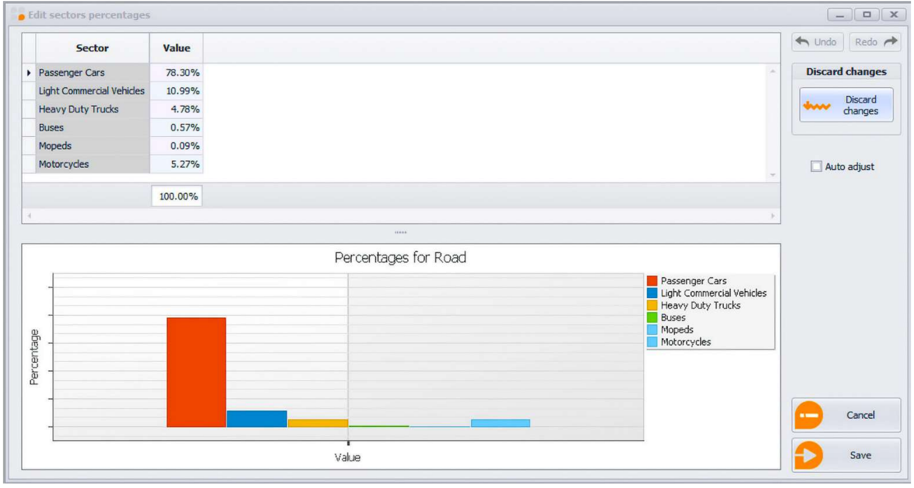
Total link types : **None**
Total hours : **None**
Total links : **1563**
GIS projection type : **EPSG:3857, Projected**

Figure 13. Data specified for each road link as required by COPERT Street Level



Link ID	Length [km]	Start LON	Start LAT	End LON	End LAT	Speed [km/h]	Volume [n/hour]
315::386	0.09927	4121.515137	1776.739136	4219.336911	1759.85196	38.53	7.01
2467::2468	0.08241	5012.24	3394.700928	4933.586914	3419.310791	14.59	143.01
3155::936	0.0154	3084.539063	2278.176025	3083.577286	2262.80939	0	0
2262::2263	0.16053	3459.353251	2507.662443	3367.150635	2639.06665	0	0
3315::3316	0.04864	3001.943115	2618.811768	3032.553223	2581.013428	37.05	3
910::2484	0.03692	4247.723806	3495.595529	4213.264061	3482.357251	0	0
2033::2224	0.04925	3575.674512	3510.532973	3621.878662	3527.588379	60.8	71.88
292::289	0.02984	5991.533272	1964.935113	6012.066751	1958.832428	25.67	52.36
47::48	0.11402	5824.169434	1926.66748	5712.78125	1902.30127	51.88	41.94
1940::1950	0.034	4233.28356	3893.350823	4250.58985	3864.090128	43.38	12.98
250::2251	0.08239	4104.679199	3277.737305	4179.024414	3313.250732	29.89	9.63
3311::3312	0.023	2542.487549	2677.290039	2562.57637	2688.487125	0	0
307::319	0.08088	4831.89209	1755.895142	4758.270063	1789.386659	34.71	12.58
1550::1700	0.04041	4452.041016	3651.346191	4414.742188	3666.897949	54.8	47.51
192::173	0.15217	5122.696777	2033.484253	5137.707241	2184.90854	39.54	10.9
3251::3252	0.05142	2676.324707	2741.965332	2628.769775	2722.419678	69.93	56.79
3200::3201	0.02053	3668.685242	1913.432194	3648.546387	1909.442749	42.24	11.19

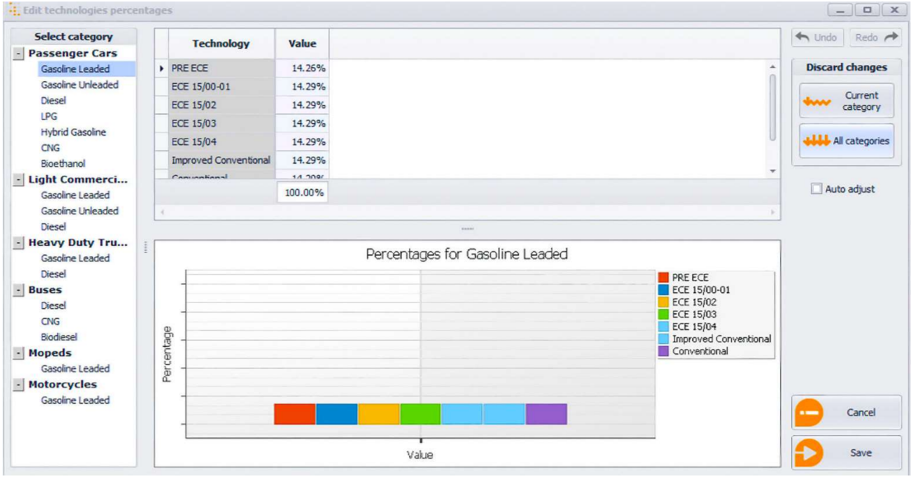
Figure 14. Sector proportion data required by COPERT Street Level



Sector	Value
Passenger Cars	78.30%
Light Commercial Vehicles	10.99%
Heavy Duty Trucks	4.78%
Buses	0.57%
Mopeds	0.09%
Motorcycles	5.27%
	100.00%

☐ Auto adjust

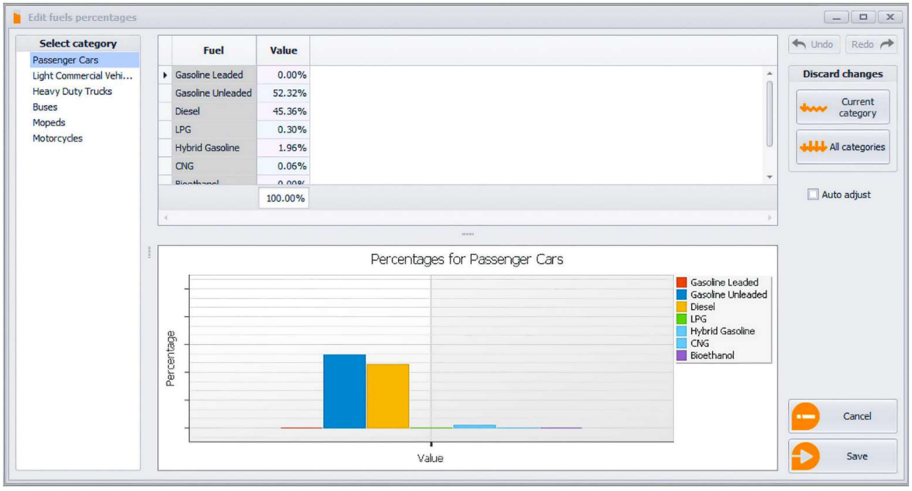
Figure 15. Engine technology as required by COPERT Street Level



Technology	Value
PRE ECE	14.26%
ECE 15/00-01	14.29%
ECE 15/02	14.29%
ECE 15/03	14.29%
ECE 15/04	14.29%
Improved Conventional	14.29%
	100.00%

☐ Auto adjust

Figure 16. Fuel percentage data of the fleet required by COPERT Street Level



Fuel	Value
Gasoline Leaded	0.00%
Gasoline Unleaded	52.32%
Diesel	45.36%
LPG	0.30%
Hybrid Gasoline	1.96%
CNG	0.06%
	100.00%

☐ Auto adjust

3.6. Air Dispersion Modelling

3.6.1. Overview

With the traffic modelling part, the impacts of the proposed traffic limiting strategies were measured based on traffic related parameters. The outputs from the traffic model were inserted into the emissions model to establish emission factors for the vehicle traffic using each considered road link.

Subsequently, the impacts/changes in air quality associated with the proposed schemes were quantified using a commercially-available air pollution dispersion modelling software, namely, BREEZE ROADS™ Version 5.1.8 (Trinity Consultants, 2024), which employs the CALINE series of models.

The scope of this section is to detail the process of how traffic emissions data was used within the dispersion modelling software to study changes in pollutant concentration levels.

3.6.2. Dispersion Models and Software Selection

BREEZE Roads™ is a software tool used to model the diffusion of inert pollutants from linear road sources, particularly CO, $PM_{2.5}$ and NO_2. The software has three inbuilt dispersion models, these being CALINE4, CAL3QHC and CAL3QHCR, which made it an optimal choice for this study (Joshua et al., 2022). CALINE4 in particular was used as it was developed as a line source model which is suited for semi-open street environments. This closely matches the modelling situation in Ħal Għaxaq which is characterised by low-lying urban development, with the streets being wide and open. CALINE4 also can handle modelling NO_2, which was the selected pollutant being studied.

3.6.3. Inputs

3.6.3.1 Meteorological Data

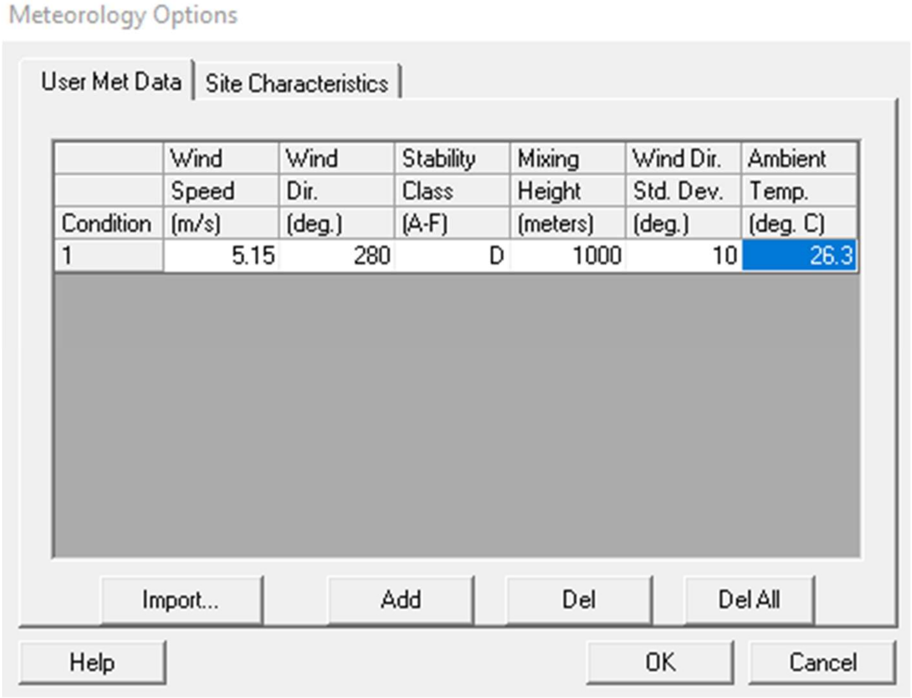
BREEZE Roads™ calculates concentrations from historical hourly or user-specified meteorological data. Users need to input an hourly meteorological data file for CAL3QHCR or a single meteorological observation for CAL3QHC or CALINE4 (Trinity Consultants, 2001). In this case, monthly average meteorological data for 2023 was acquired from the Malta Meteorological Office (MET Office, 2024)

For CALINE4, the following meteorological conditions needed to be specified (refer to Figure 17);

- Wind Speed – Wind speed typically measured from 10m above ground level.

- Wind Direction – Wind direction should be inputted using standard meteorological conventions. Meaning, a 180-degree wind is blowing from due south, transporting pollutants to the north.
- Stability Class – Pasquill Stability categories need to be defined, with category A representing very unstable conditions, D representing neutral stability, and F representing very stable conditions.
- Mixing Height – The height of the top of the mixing layer for each condition.
- Ambient Temperature – The average yearly average during the day.

Figure 17. User defined meteorological data within BREEZE Roads

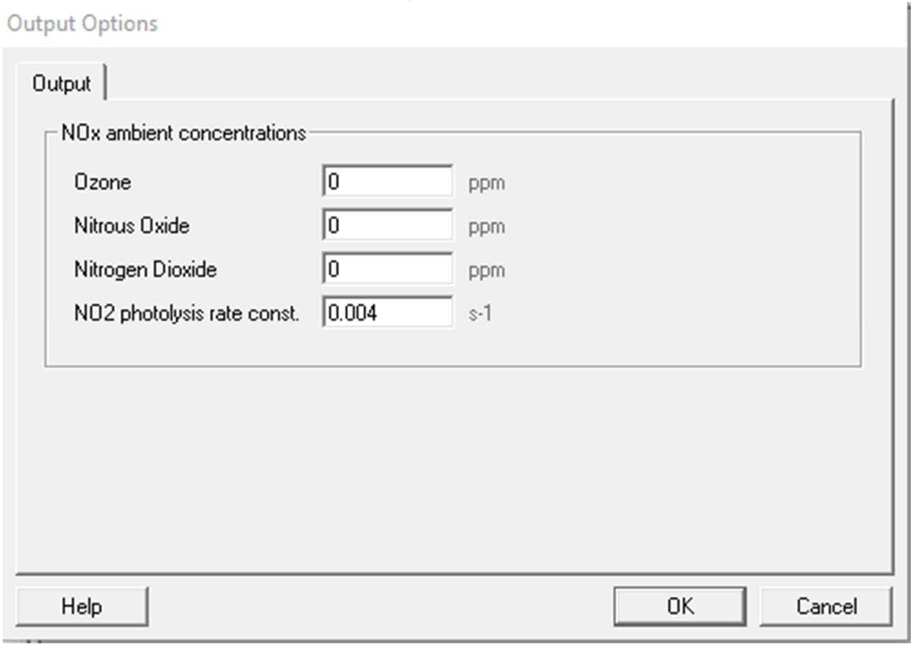


Condition	Wind Speed (m/s)	Wind Dir. (deg.)	Stability Class (A-F)	Mixing Height (meters)	Wind Dir. Std. Dev. (deg.)	Ambient Temp. (deg. C)
1	5.15	280	D	1000	10	26.3

3.6.3.2 Background Concentrations

For CALINE4, NO_2 ambient concentrations have to be inputted with consideration given to several parameters. Figure 18 below shows the requested parameters in the software dialogue box. While the other parameters were left as default, the Nitrogen Dioxide was an input that was required, this being the value that represents the NO_2 concentration levels without the contribution of traffic sources. Therefore, this background concentration value would be added to the traffic generated levels in order to get the total NO_2 concentration levels in the air. From data gathered by the ERA's real-time air quality station at Żejtun (this being characterised as an urban background site), it was found that the average yearly background concentration for 2023 was 13.65μg/m^3

Figure 18. User defined ambient concentration parameters within BREEZE Roads

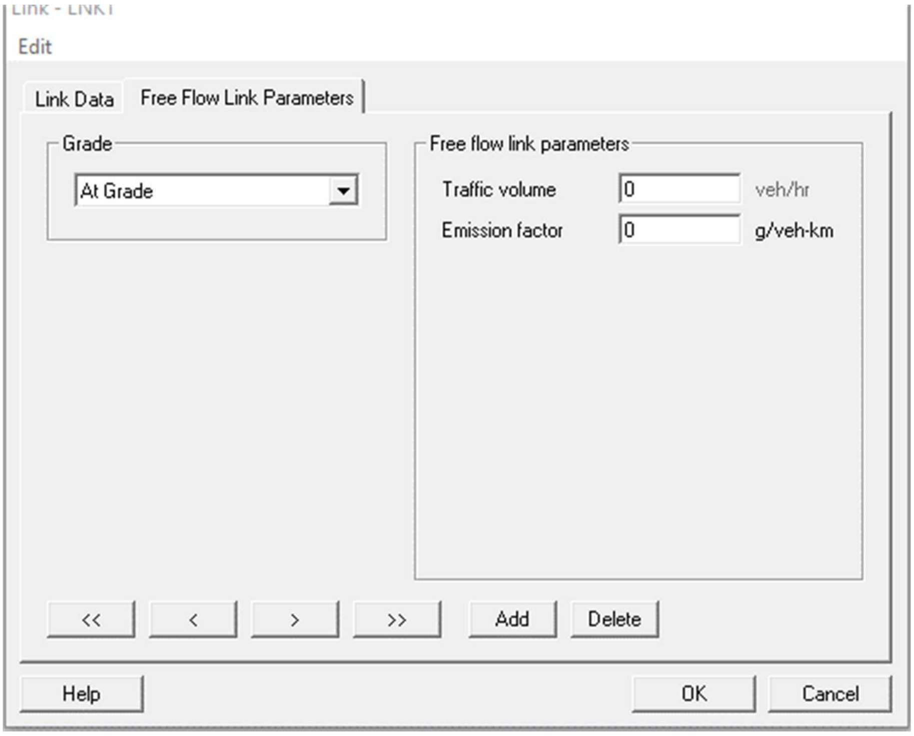


Ozone: 0 ppm
Nitrous Oxide: 0 ppm
Nitrogen Dioxide: 0 ppm
NO2 photolysis rate const.: 0.004 s-1

3.6.3.3 Defining Road Links

Constructing a model involves defining links that represent the roadway being studied. Entering data for each link first requires defining whether it is a Free-flow or a Queue link (shown in Figure 19). Vehicles in a Free-flow link are assumed to travel without delay, while vehicles in a Queue link are expected to be idling on these links (Trinity Consultants, 2001).

Figure 19. User defined Free-flow Link parameters within BREEZE Roads

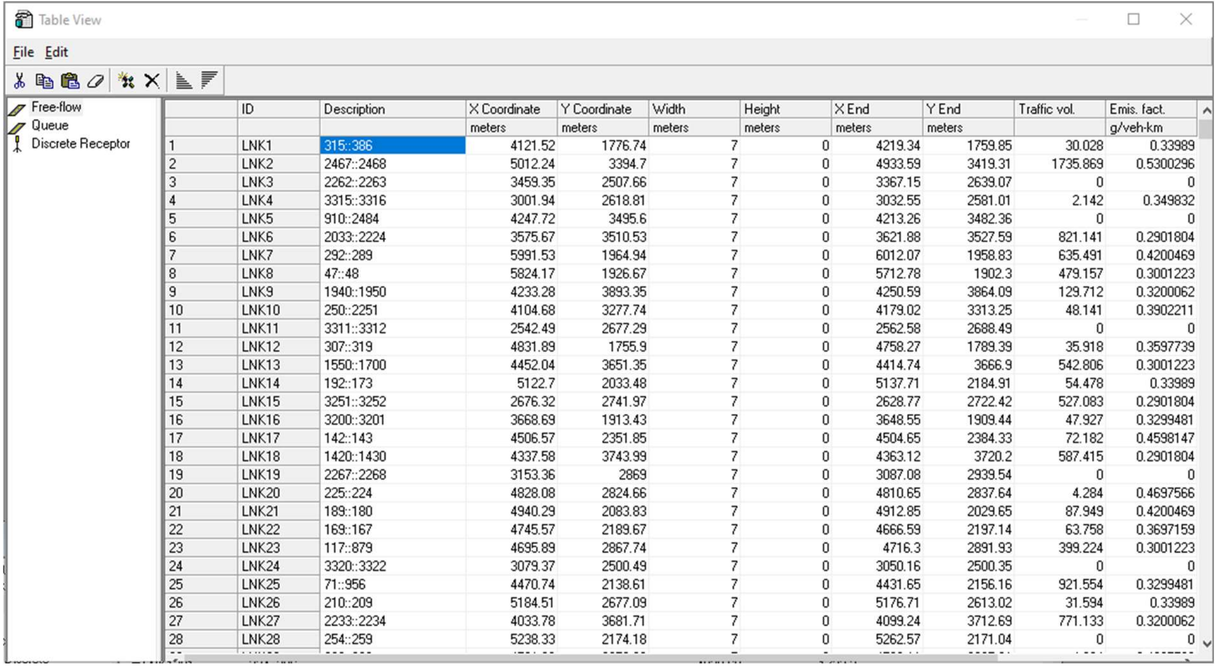


Grade: At Grade
Traffic volume: 0 veh/hr
Emission factor: 0 g/veh-km

With a Queue link, the user can specify additional traffic parameters associated with traffic-light junctions. However, given that the traffic congestion at the area of study is not caused by traffic-lights, it was decided to characterise the modelled links as Free-flow links.

The cartesian coordinates of the road network defined within the traffic model were exported and used to define the road network in the dispersion model. Additionally, each road link was given their associated emission factor (gathered from the emission modelling software) and traffic volume (shown in Figure 20).

Figure 20. A sample of defined Free-flow Links making up the network within BREEZE Roads

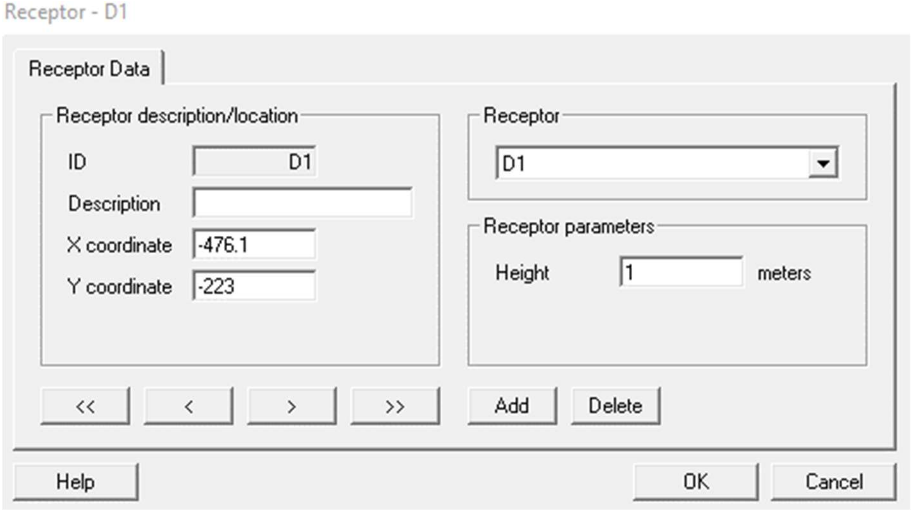


	ID	Description	X Coordinate meters	Y Coordinate meters	Width meters	Height meters	X End meters	Y End meters	Traffic vol.	Emis. fact. g/veh-km
1	LNK1	315::386	4121.52	1776.74	7	0	4219.34	1759.85	30.028	0.33989
2	LNK2	2467::2468	5012.24	3394.7	7	0	4933.59	3419.31	1735.869	0.5300296
3	LNK3	2262::2263	3459.35	2507.66	7	0	3367.15	2639.07	0	0
4	LNK4	3315::3316	3001.94	2618.81	7	0	3032.55	2581.01	2.142	0.349832
5	LNK5	910::2484	4247.72	3495.6	7	0	4213.26	3482.36	0	0
6	LNK6	2033::2224	3575.67	3510.53	7	0	3621.88	3527.59	821.141	0.2901804
7	LNK7	292::289	5991.53	1964.94	7	0	6012.07	1958.83	635.491	0.4200469
8	LNK8	47::48	5824.17	1926.67	7	0	5712.78	1902.3	479.157	0.3001223
9	LNK9	1940::1950	4233.28	3893.35	7	0	4250.59	3864.09	129.712	0.3200062
10	LNK10	250::2251	4104.68	3277.74	7	0	4179.02	3313.25	48.141	0.3902211
11	LNK11	3311::3312	2542.49	2677.29	7	0	2562.58	2688.49	0	0
12	LNK12	307::319	4831.89	1755.9	7	0	4758.27	1789.39	35.918	0.3597739
13	LNK13	1550::1700	4452.04	3651.35	7	0	4414.74	3666.9	542.806	0.3001223
14	LNK14	192::173	5122.7	2033.48	7	0	5137.71	2184.91	54.478	0.33989
15	LNK15	3251::3252	2676.32	2741.97	7	0	2628.77	2722.42	527.083	0.2901804
16	LNK16	3200::3201	3668.69	1913.43	7	0	3648.55	1909.44	47.927	0.3299481
17	LNK17	142::143	4506.57	2351.85	7	0	4504.65	2384.33	72.182	0.4598147
18	LNK18	1420::1430	4337.58	3743.99	7	0	4363.12	3720.2	587.415	0.2901804
19	LNK19	2267::2268	3153.36	2869	7	0	3087.08	2939.54	0	0
20	LNK20	225::224	4828.08	2824.66	7	0	4810.65	2837.64	4.284	0.4697566
21	LNK21	189::180	4940.29	2083.83	7	0	4912.85	2029.65	87.949	0.4200469
22	LNK22	169::167	4745.57	2189.67	7	0	4666.59	2197.14	63.758	0.3697159
23	LNK23	117::879	4695.89	2867.74	7	0	4716.3	2891.93	399.224	0.3001223
24	LNK24	3320::3322	3079.37	2500.49	7	0	3050.16	2500.35	0	0
25	LNK25	71::956	4470.74	2138.61	7	0	4431.65	2156.16	921.554	0.3299481
26	LNK26	210::209	5184.51	2677.09	7	0	5176.71	2613.02	31.594	0.33989
27	LNK27	2233::2234	4033.78	3681.71	7	0	4099.24	3712.69	771.133	0.3200062
28	LNK28	254::259	5238.33	2174.18	7	0	5262.57	2171.04	0	0

3.6.3.4 Receptors

Figures 21 and 22 show how receptors were defined in the software. Receptors are the instruments within the model that measure pollutant concentration at its location. A receptor grid with 50m spacing was defined across the modelled road network.

Figure 21. User defined Receptor Data for an example receptor within BREEZE Roads



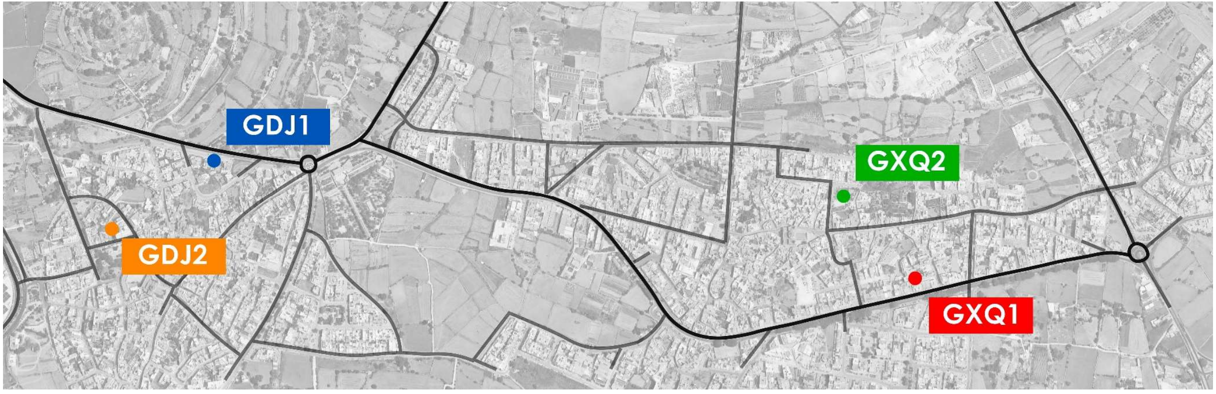
ID: D1
Description:
X coordinate: -476.1
Y coordinate: -223
Receptor: D1
Height: 1 meters

Figure 22. Road network and Receptor Grid (yellow) represented within BREEZE Roads

3.6.4. Calibration

The calibration of the model involved testing and changing variables in order to get the model's pollutant concentration values to match with real-world values gathered from the ERA's passive diffusion tubes. The calibration was conducted over four receptors that represented the positioning of four of these real-world receptors (GXQ1, GXQ2, GDJ1 and GDJ2) (shown in Figure 23). GXQ1 was the primary receptor as this is situated right on Dawret Ħal Għaxaq road. A successful calibration was considered if modelled receptor values come within 20% of their real-world counterparts.

Figure 23. Map showing the positions of the four real-world receptors



CHAPTER 4 - RESULTS

4.1. Overview

As outlined in Chapter 1, the scope of this research was to explore digital modelling methods that can provide a comprehensive understanding of the impact of traffic on air quality. Particularly, the adopted approach which is documented in Chapter 3 was used to measure traffic and air quality changes after the implementation of traffic limiting strategies within the Maltese context.

This chapter intends to first document and then present an analysis of the results from the traffic, emission, and air dispersion modelling process, with particular interest given to the type of data that can be produced. These results were obtained through the modelling of the present-day situation, and two experimental scenarios, in an area of the Maltese road network. The comparison of extracted results from the different conditions is intended to demonstrate how this modelling process may be useful in choosing the most effective strategy when addressing issues with traffic-generated emissions in Malta.

For reference, the three scenarios are described below:

- The ‘Do-Nothing’ scenario, which aimed to accurately depict the present-day situation, for each modelling step (referred to as Scenario 1).
- The ‘Do-Something 1’ scenario, which simulated an experimental scenario that involved the restriction of through-traffic passing through the locality of Ħal Għaxaq, specifically on Dawret Ħal Għaxaq road (referred to as Scenario 2).
- The ‘Do-Something 2’ scenario, which simulated an experimental scenario that sees the reduction of single-occupant vehicles through the implementation of a carpooling scheme (referred to as Scenario 3).

4.2. Traffic Modelling Results

4.2.1. Overview

Using the microsimulation traffic model for the study area, the changes in traffic behaviour after implementing the proposed changes recorded. Moreover, these outputs were needed for the continuation of the air quality modelling process. In this section, the performance of the traffic network was documented in terms of three main indicators, namely vehicle turn counts at junctions, traffic volumes and average speed.

4.2.2. Junction Turn Movements

Vehicle turn movements have been compared at different junctions. The junctions close to where the network change was implemented (adjacent to Dawret Ħal Għaxaq road) were of particular interest. An example of this comparison is given below for Junction A, with the comparisons for the other mentioned junctions (labelled in Figure 24) being given in Appendix B. Figure 25 shows a turn movement diagram which labels each of the recorded movements from each of the junction arms, with Table 6 documenting the number of vehicles making each movement within the modelled peak hour.

Figure 24. Locations of the junctions with comparison of turn movements

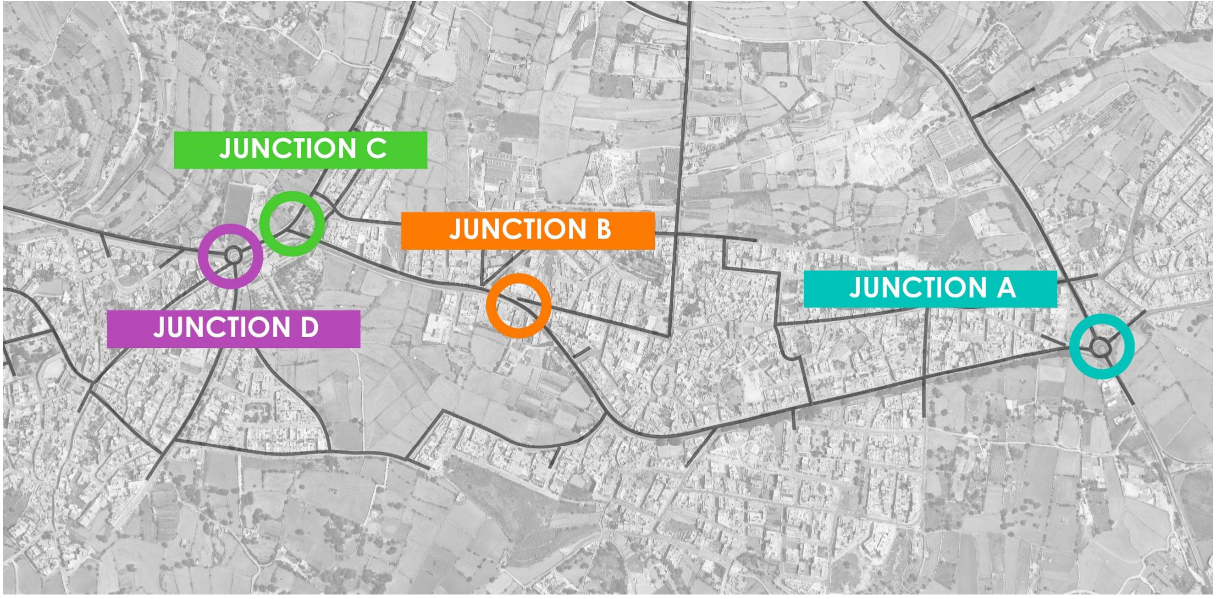


Figure 25. Junction turn movements diagram at Junction A

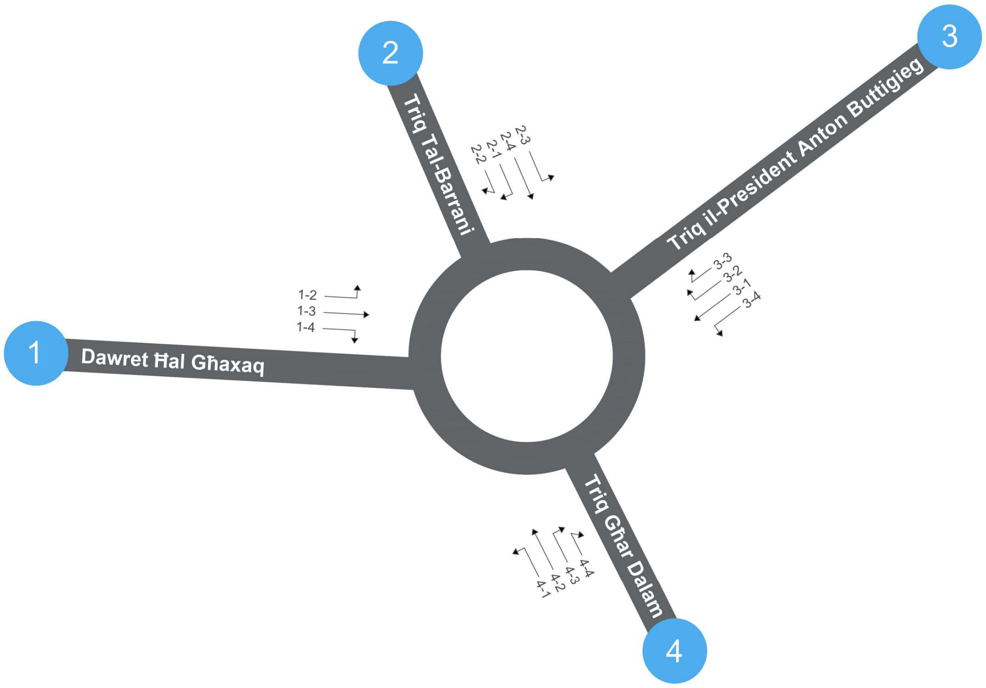


Table 6. Junction turn movements at Junction A compared between scenarios

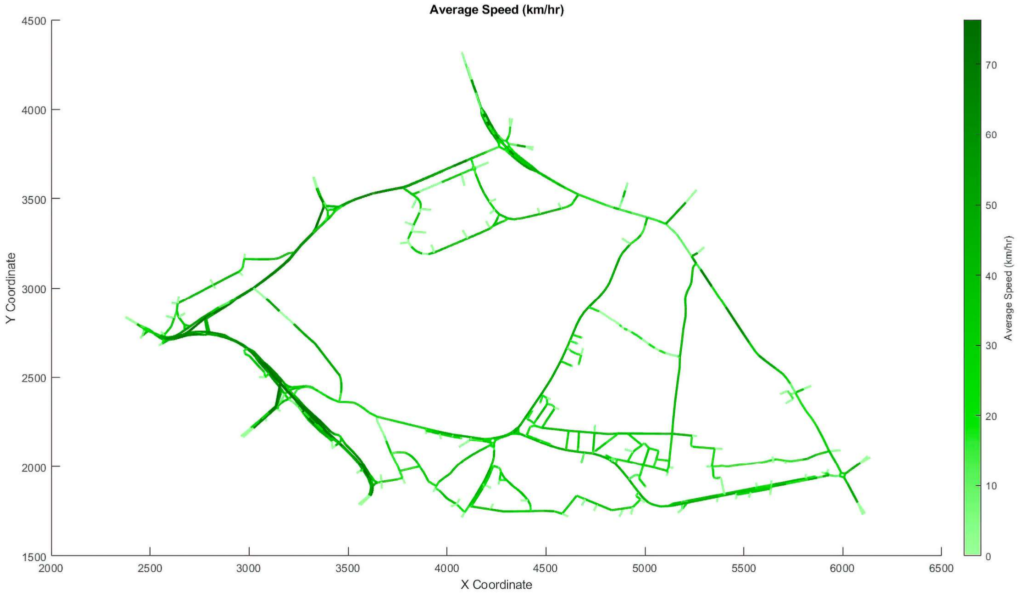
JUNCTION A			
Turns	**Do-Nothing**	**Do-Something 1**	**Do-Something 2**
1-2	136	76	131
1-3	133	38	131
1-4	139	39	139
2-1	115	51	108
2-2	104	103	86
2-3	100	97	92
2-4	188	148	181
3-1	88	9	86
3-2	292	311	297
3-3	2	2	2
3-4	11	10	10
4-1	341	28	381
4-2	571	634	602
4-3	5	4	5
4-4	3	2	3

4.2.3. Link Average Speed

Link average speed is an indicator for traffic congestion, with an average speed lower than the road link's posted speed limit meaning congestion. Using the traffic model, the link average speeds of the entire modelled network were found for the 'Do-Nothing' and the two 'Do-Something' scenarios, and differences between scenarios could be identified.

Figure 26 is a heatmap that shows the variation of mean average speed across the modelled network for the 'Do-Nothing' scenario (Scenario 1) during the peak hour, whereby darker green indicates higher speeds, and lighter green indicates lower speeds.

Figure 26. Modelled Road Network Heatmap for Average Speed in Scenario 1



After documenting the average speed results for the three scenarios independently, the percentage differences between average speed values of the 'Do-Nothing' scenario (the baseline scenario) and the two 'Do-Something' scenarios was conducted. These findings were then plotted onto heatmaps of the modelled road network. Figure 27 represents differences between scenarios 1 and 2, and Figure 28 represents differences between scenarios 1 and 3.

Figure 27. Heatmap showing the percentage difference in average speed between Scenarios 1 & 2

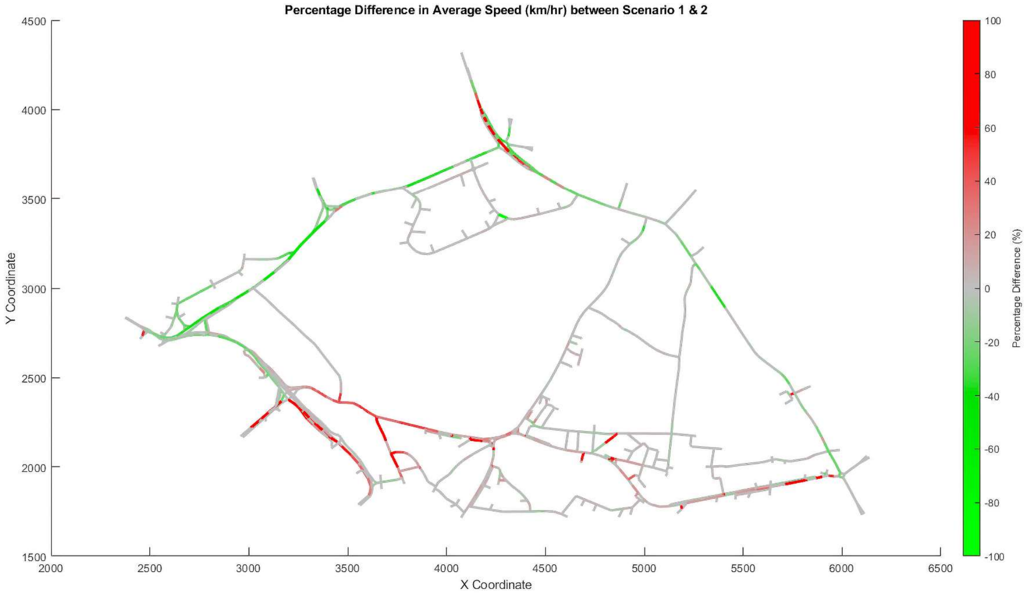
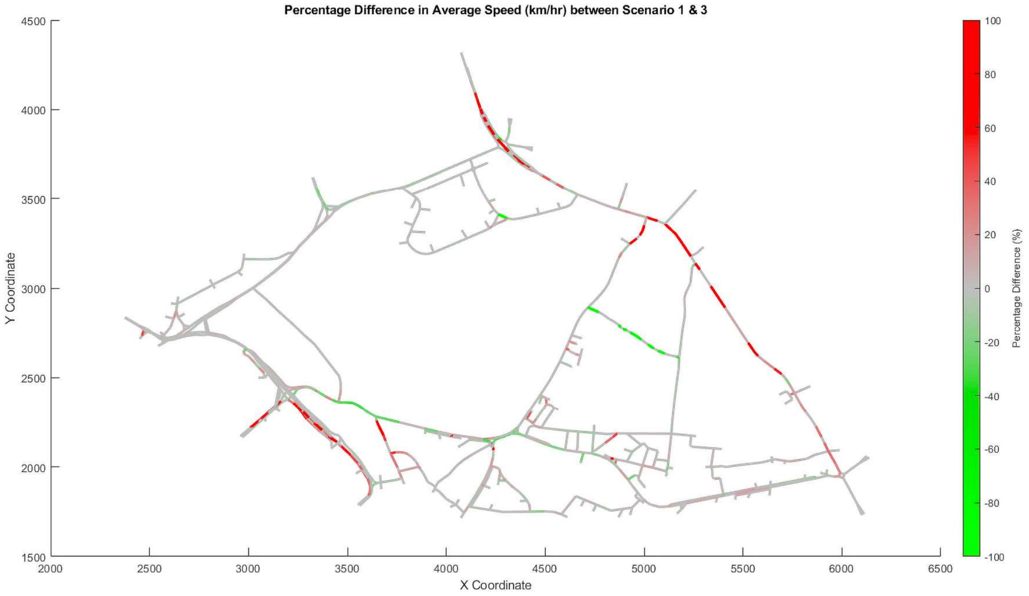


Figure 28. Heatmap showing the percentage difference in average speed between Scenarios 1 & 3

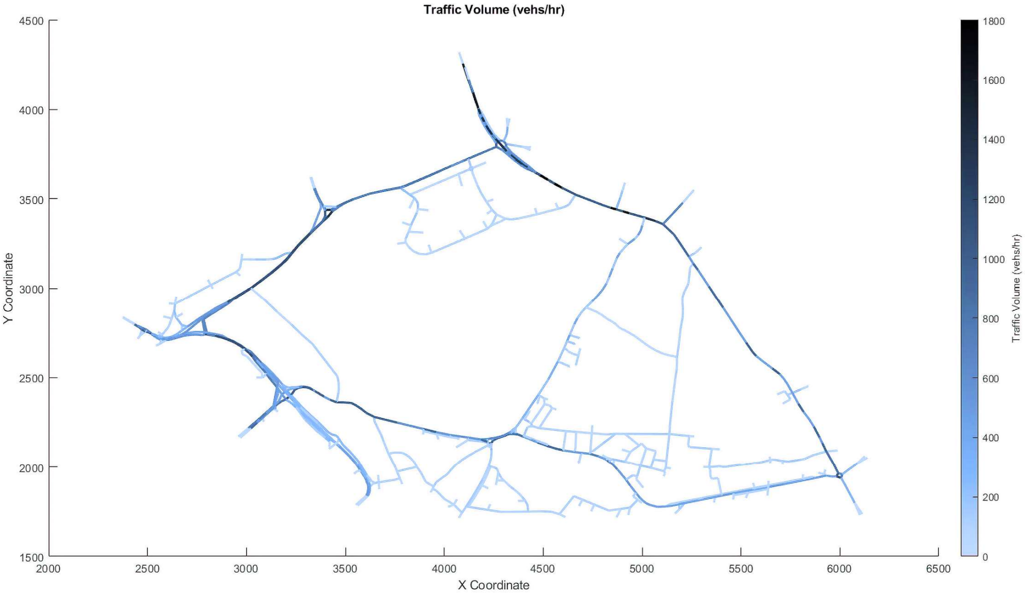


4.2.4. Traffic Volume

Traffic volume represents the volume of traffic that passes through each road link in an hour. With the traffic model, traffic volume at peak hour for each link in the network was found. As described in section 3.4.7 (p.g.31), these peak hour traffic volumes were converted to hourly average for month, with these being used in the proceeding modelling steps.

These traffic volume results for Scenario 1 were displayed on a heatmap across the modelled network (refer to Figure 29), with darker blue indicating higher volumes, and lighter blue indicating lower volumes. This map clearly shows which roads in the modelled network handle the most traffic volumes.

Figure 29. Modelled Road Network Heatmap for Traffic Volume in Scenario 1



A similar comparison to average speed was conducted for traffic volume, whereby the change in traffic volumes was quantified and displayed on a heatmap. Figure 30 shows this difference between scenarios 1 and 2, and Figure 31 shows it between scenarios 1 and 3.

Figure 30. Heatmap showing the percentage difference in traffic volume between Scenarios 1 & 2

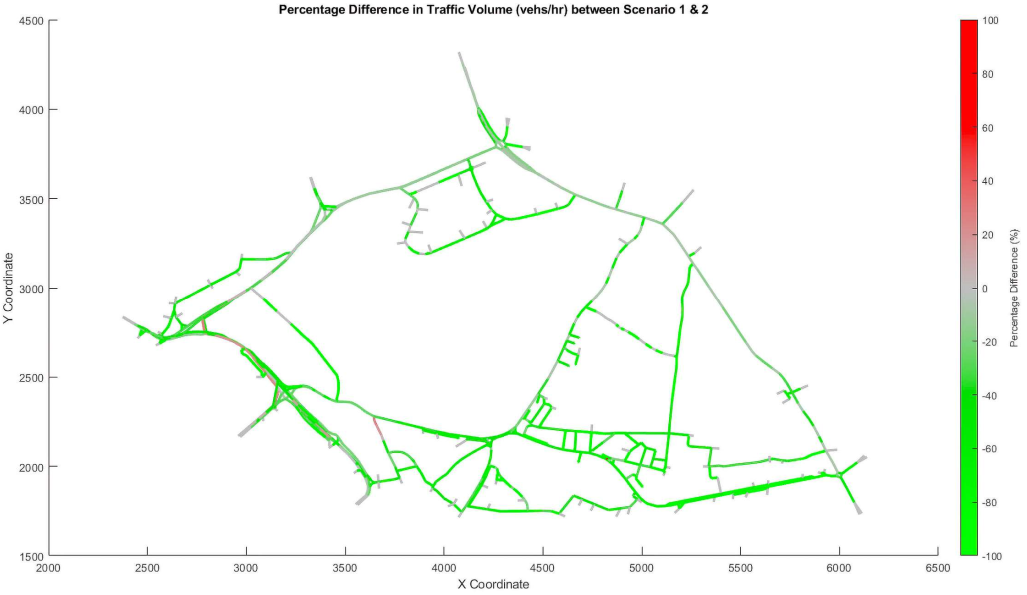
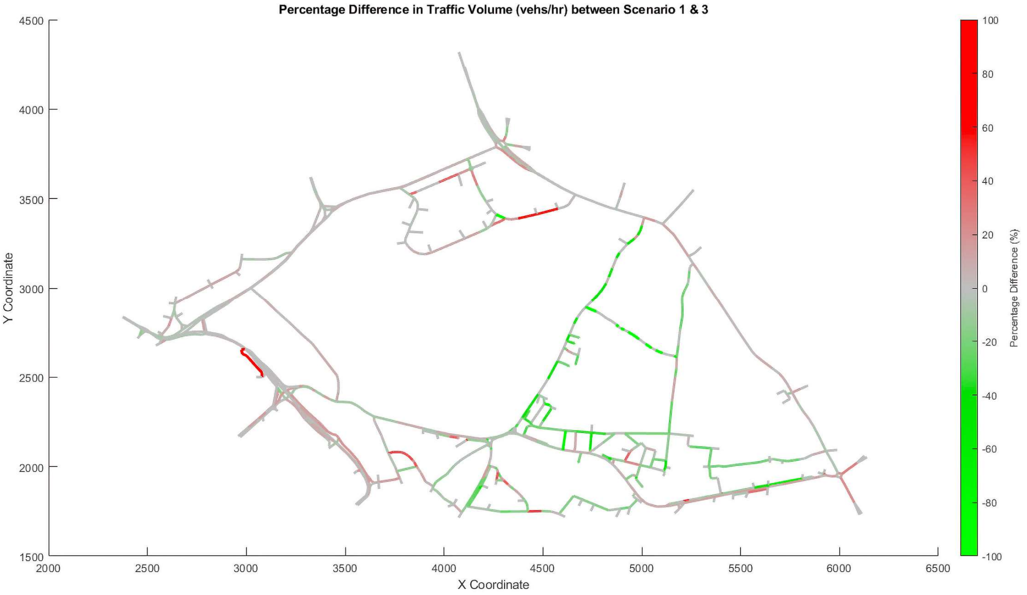


Figure 31. Heatmap showing the percentage difference in traffic volume between Scenarios 1 & 3



A more specific comparison of results was conducted on seven benchmark roads, outlined in Table 7 and in Figure 32. These benchmark roads represent important links within the network, hence their choice for more detailed comparison, with traffic volumes being documented in Figure 33 for each of the three scenarios, for each direction of these roads.

Figure 32. The stretches making up the seven benchmark roads within the study area

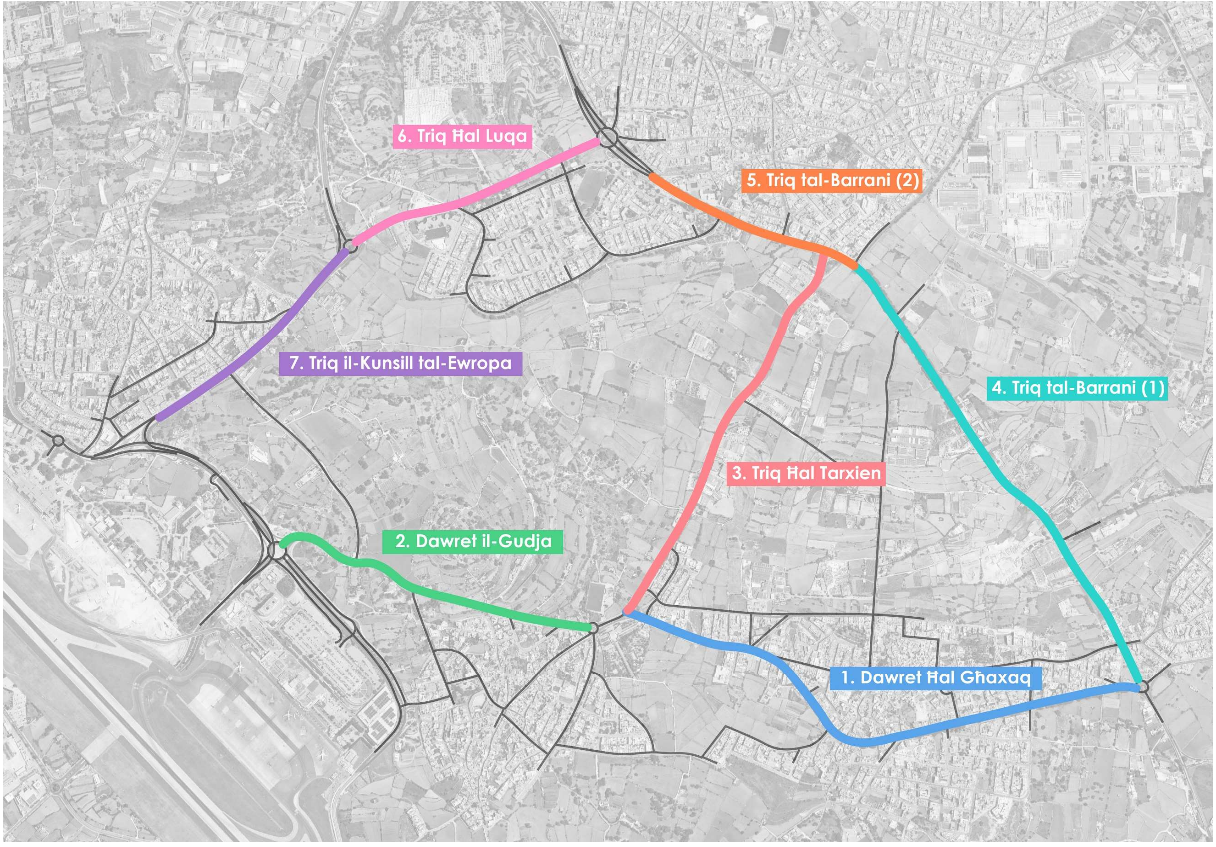
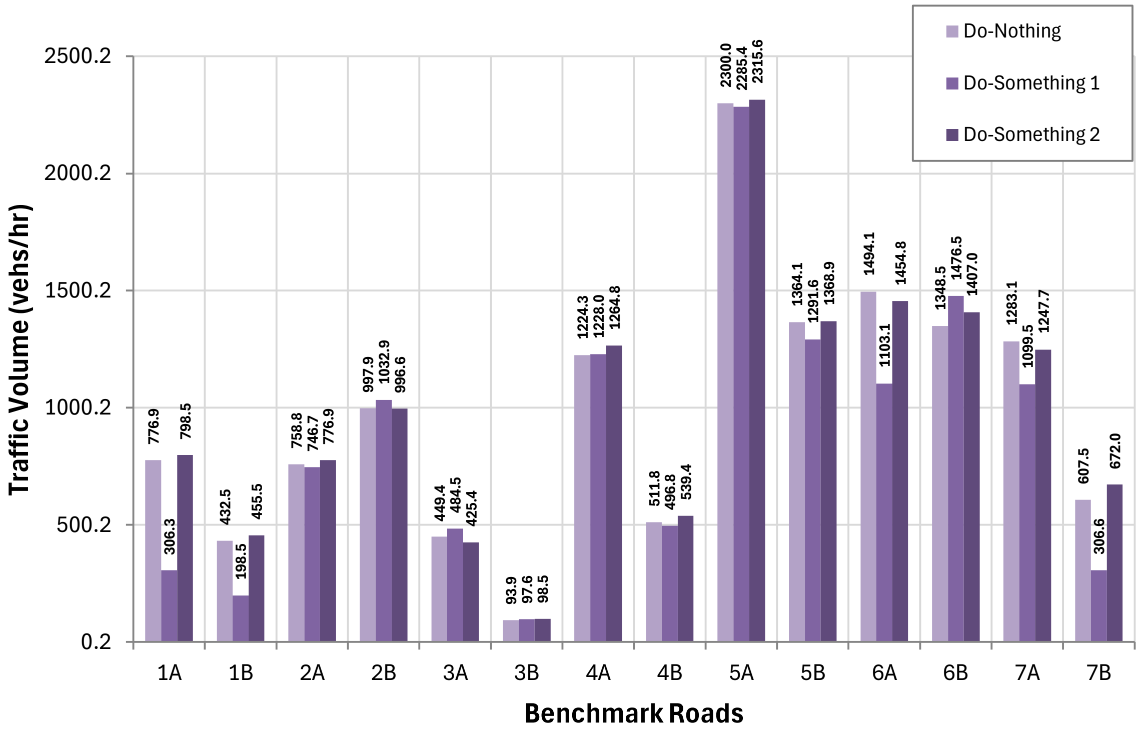


Table 7. Seven benchmark roads

Road ID	Road Name
1	Dawret Ħal Għaxaq
2	Dawret il-Gudja
3	Triq Ħal Tarxien
4	Triq tal-Barrani (Section 1)
5	Triq tal-Barrani (Section 2)
6	Triq Ħal Luqa
7	Triq il-Kunsill tal-Ewropa

Figure 33. Comparison of traffic volumes between scenarios for each benchmark road



Note: A = Traffic flowing West/North, B = Traffic flowing East/South

Several observations can be made by the documented comparisons. Most of the roads in the network, and all of the seven benchmark roads, seem to exhibit a minimal difference in volume between Scenario 1 and Scenario 3. Changes in traffic volume between scenarios 1 and 2 can be seen on some roads, namely Dawret Ħal Għaxaq (1A and 1B), Triq Ħal Luqa (6A and 6B), and Triq il-Kunsill tal-Ewropa (7A and 7B). Specifically, the reduction in volume on Dawret Ħal Għaxaq road was due to the imposed restriction measure in Scenario 2. However, the changes in volume exhibited on other roads can be attributed to an increased amount of traffic that was forced to find alternative routes. This increase in traffic causes both a rise and a decrease in volume, whereby this increase on roads that were at capacity contributed to a decline in volumes, while roads that were not at capacity saw a rise in volumes.

4.3. Emissions Modelling Results

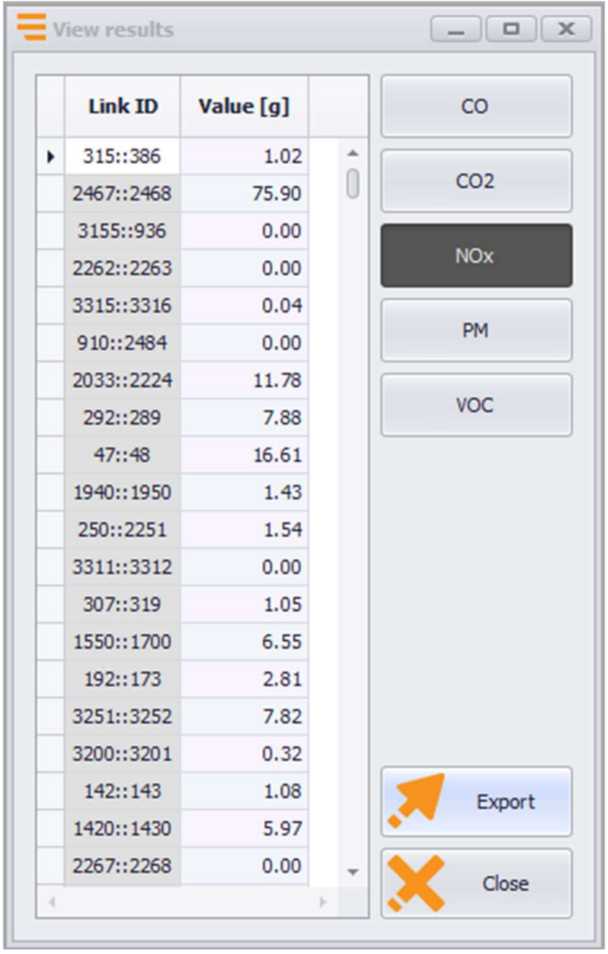
4.3.1. Overview

As stated in Chapter 3, COPERT Street Level™ was used to gather the emission factors (EF) for each road link in the studied road network. The generated outputs include the sum of the pollutant load (in grams) from every vehicle passing from a specific road link. While in this study the pollutant load was used to find concentration levels, certain pollution standards limit emission based on this metric (as discussed in section 2.2, p.g.5). From these pollutant load values the model generates the EF (in grams per vehicle-kilometre) for an average vehicle that passes through the length of that road link.

4.3.2. Emission Modelling Inputs and Outputs

Using the parameters specified in section 3.5.3 (p.g.32), namely link length, average speed, traffic volume and vehicle type proportions, the software was able to generate the total pollutant load (in grams) vehicles travelling on a road link produce in an hour (Figure 34). While being able to produce results for several pollutants, only NO_X results were of interest in this study.

Figure 34. Pollutant Load (g) for each road link within COPERT Street Level



Link ID	Value [g]
315::386	1.02
2467::2468	75.90
3155::936	0.00
2262::2263	0.00
3315::3316	0.04
910::2484	0.00
2033::2224	11.78
292::289	7.88
47::48	16.61
1940::1950	1.43
250::2251	1.54
3311::3312	0.00
307::319	1.05
1550::1700	6.55
192::173	2.81
3251::3252	7.82
3200::3201	0.32
142::143	1.08
1420::1430	5.97
2267::2268	0.00

The software also generated a map showing the emission levels generated by all road traffic per the length of the link in kilometres (Figure 35). Tables 8, 9 and 10 document the emission model inputs and outputs for the three scenarios. As referred to in Figure 32, benchmark roads are denoted by numbers, with the tables adding ‘A’ to refer to traffic flowing west/north and ‘B’ to refer to traffic flowing east/south.

Figure 35. Total emission generated per length of each link (kg/km) within COPERT Street Level

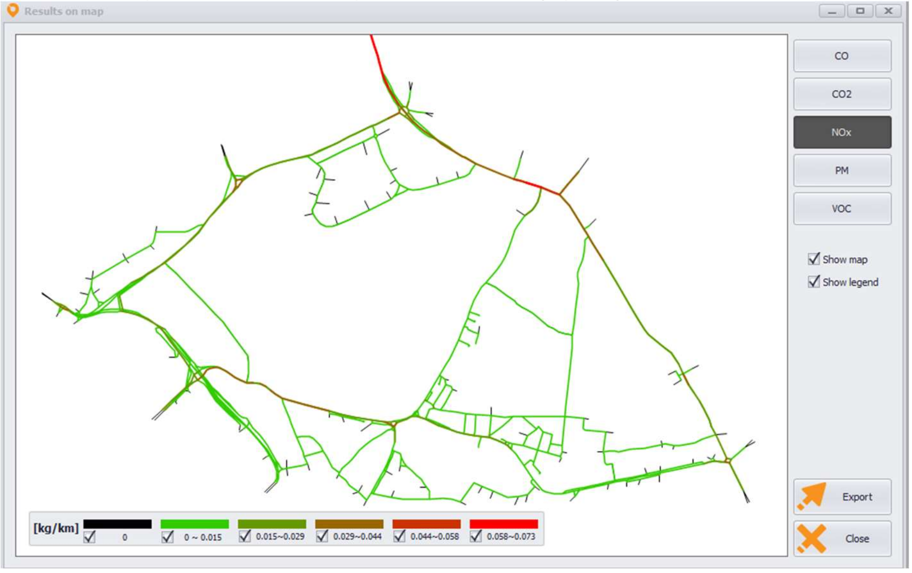


Table 8. Model Input & Outputs used during the emissions modelling process for Scenario 1

Benchmark Roads	**MODEL INPUTS**			**MODEL OUTPUTS**	
	Road Length (km)	**Traffic Volume (veh/hr)**	**Average Speed (km/hr)**	**NO_X Pollutant Load (g)**	**Emission Factor (g/veh-km)**
1A	1.75	621.86	45.73	336.95	0.32
1B		440.16	36.67	274.12	0.36
2A	1.00	971.82	26.63	385.23	0.41
2B		403.69	28.19	170.14	0.26
3A	1.36	131.90	46.54	58.16	0.32
3B		377.24	41.63	173.42	0.35
4A	1.66	936.01	27.10	645.83	0.42
4B		465.94	43.00	269.86	0.36
5A	0.72	1712.76	33.31	473.15	0.39
5B		662.71	11.32	267.17	0.32
6A	0.77	602.96	55.68	168.01	0.31
6B		794.60	49.47	223.95	0.32
7A	0.70	1142.96	63.05	220.42	0.29
7B		1028.66	55.51	221.84	0.32

Table 9. Model Input & Outputs used during the emissions modelling process for Scenario 2

Benchmark Roads	**MODEL INPUTS**			**MODEL OUTPUTS**	
	Road Length (km)	**Traffic Volume (veh/hr)**	**Average Speed (km/hr)**	**NO_X Pollutant Load (g)**	**Emission Factor (g/veh-km)**
1A	1.75	213.66	45.65	110.67	0.32
1B		146.70	43.07	81.92	0.33
2A	1.00	695.27	35.65	235.86	0.36
2B		166.12	34.33	63.34	0.24
3A	1.36	68.75	47.13	31.38	0.32
3B		349.12	41.04	162.27	0.35
4A	1.66	867.19	23.17	645.27	0.45
4B		340.46	42.26	193.73	0.36
5A	0.72	1639.50	37.24	439.08	0.37
5B		575.00	10.13	244.27	0.33
6A	0.77	528.88	56.42	146.24	0.31
6B		687.38	32.06	226.14	0.38
7A	0.70	781.20	64.09	150.60	0.29
7B		1043.25	26.71	299.25	0.42

Table 10. Model Input & Outputs used during the emissions modelling process for Scenario 3

Benchmark Roads	**MODEL INPUTS**			**MODEL OUTPUTS**	
	Road Length (km)	**Traffic Volume (veh/hr)**	**Average Speed (km/hr)**	**NO_X Pollutant Load (g)**	**Emission Factor (g/veh-km)**
1A	1.75	622.39	43.70	347.61	0.33
1B		478.30	38.85	292.97	0.36
2A	1.00	896.32	20.61	403.15	0.46
2B		443.89	31.86	177.33	0.25
3A	1.36	134.56	46.83	58.95	0.32
3B		202.48	46.49	86.39	0.32
4A	1.66	947.59	49.27	511.34	0.33
4B		477.73	45.11	274.06	0.35
5A	0.72	1722.35	43.36	422.74	0.34
5B		666.80	11.63	265.79	0.31
6A	0.77	636.73	55.53	177.23	0.31
6B		825.07	45.88	237.05	0.33
7A	0.70	1134.61	63.97	218.77	0.29
7B		1071.94	56.31	229.53	0.32

4.3.3. Comparing and Analysing Emissions Results

The process was repeated for the three tested scenarios. While inputs like vehicle fleet composition and road network geometry were kept constant throughout, traffic behaviour parameters like traffic volume and average speed, extracted from the traffic modelling process, were changed for each scenario.

Similar to the traffic results, emission performance will be measured across seven benchmark roads within the modelled network. The performance indicators being compared from the emissions model include:

- The total NO_X pollutant load in grams produced by traffic along the links making up these benchmark roads within an hour.
- The mean emission factor (EF) of the benchmark road formulated by averaging the EFs of each individual link making up that road.

4.3.3.1 Pollutant Load

The heatmap in Figure 36 documents the total amount of NOx pollutant load emitted across the modelled network for the ‘Do-Nothing’ scenario (Scenario 1) during the peak hour. The darker red indicates roads where higher amounts of load (in grams) have been emitted, with the lighter reds indicate less emission. Figures 37 and 38 show the percentage difference in pollutant load between Scenario 1 and 2, and Scenario 1 and 3 respectively.

Figure 36. Modelled Road Network Heatmap for Pollutant Load in Scenario 1

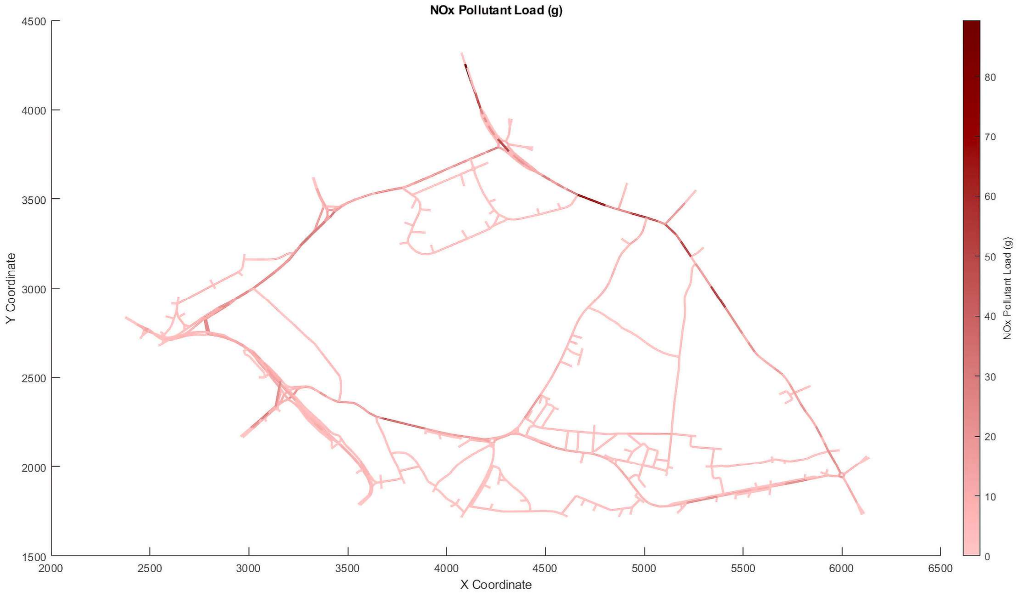


Figure 37. Heatmap showing the percentage difference in pollutant load between Scenarios 1 & 2

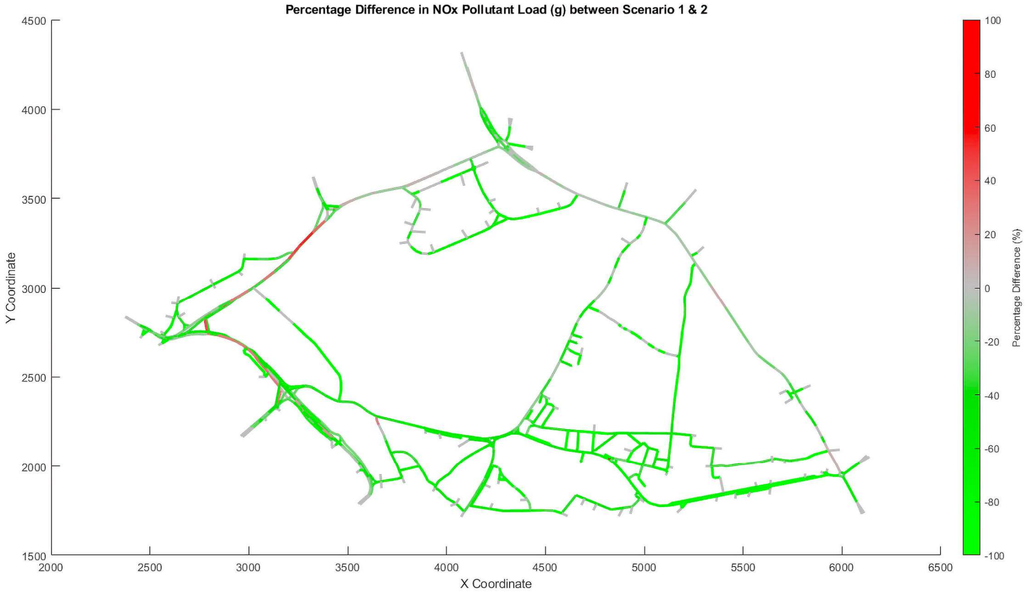
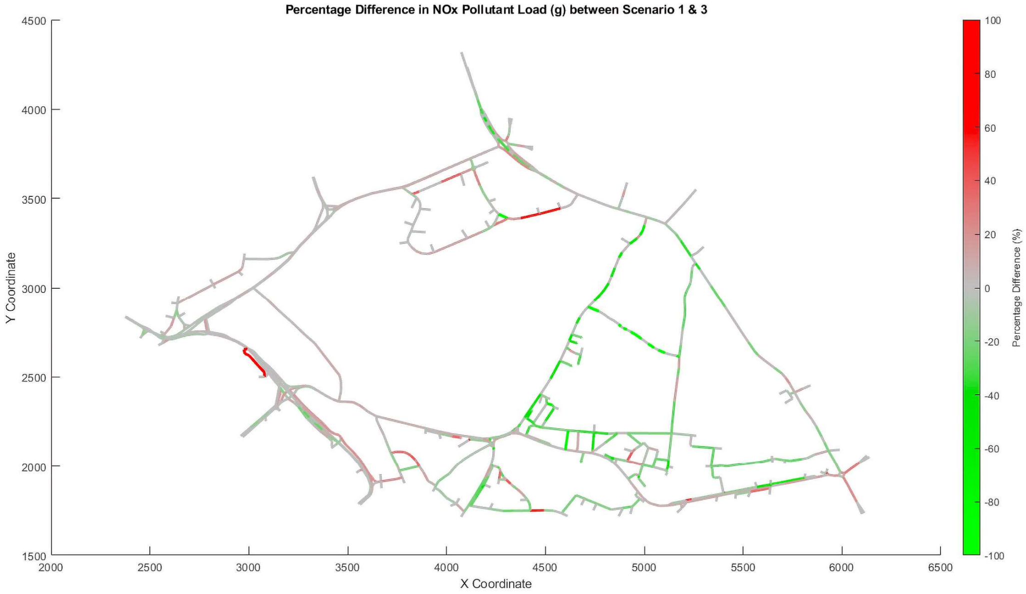
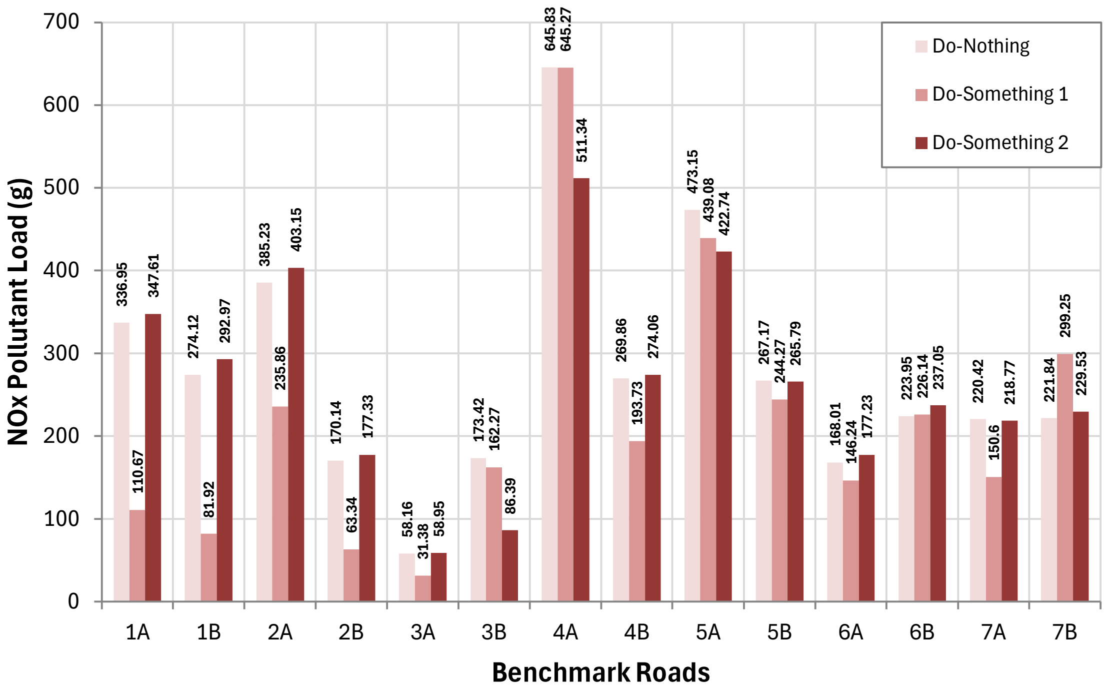


Figure 38. Heatmap showing the percentage difference in pollutant load between Scenarios 1 & 3



Similar to other documented indicators, the pollutant load values for each scenario were compared on the seven benchmark roads, this comparison being shown in Figure 39.

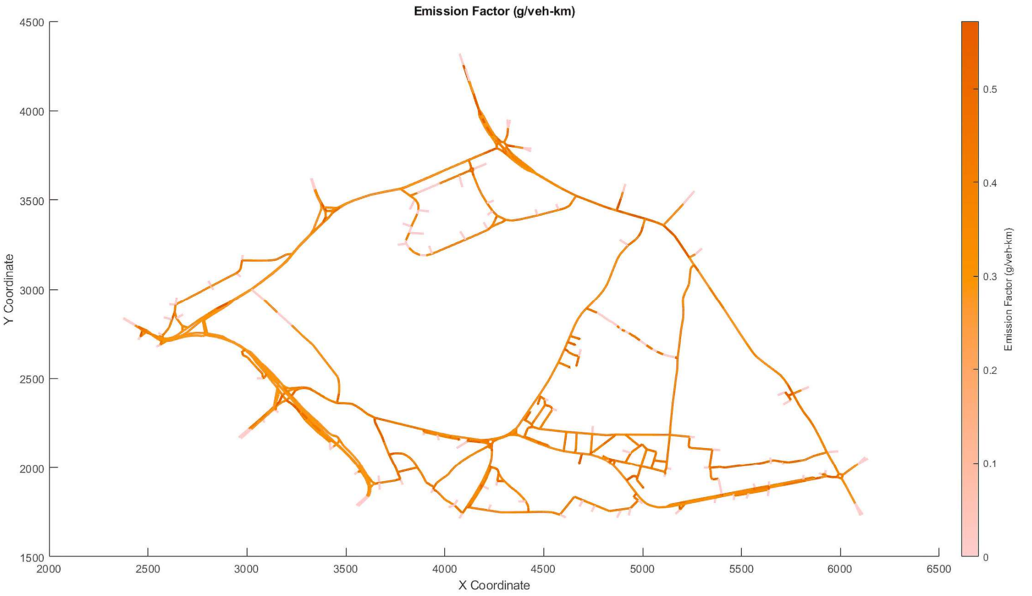
Figure 39. Comparison of NOx Pollutant Load (g) for benchmark roads, for each scenario



4.3.3.2 Emission Factors

Emission Factors (EF) are one of the main inputs used in the dispersion modelling process. Their documentation in Figure 40 shows that, while each road link has its unique EF, the differences between links, within the same scenario, are minimal. The dark orange indicates links with greater EFs than lighter orange links.

Figure 40. Modelled Road Network Heatmap for Emission Factors in Scenario 1



Differences of EF values between scenarios 1 and 2, and scenarios 1 and 3 were plotted onto heatmaps of the modelled road network. Figure 41 represents differences between scenarios 1 and 2, and Figure 42 representing differences between scenarios 1 and 3. It can be observed that there are minimal differences between each scenario. This is the case because vehicle fleet composition is a primary influence on EFs, with this being unchanged between scenarios.

Figure 41. Heatmap showing the percentage difference in EFs between Scenarios 1 & 2

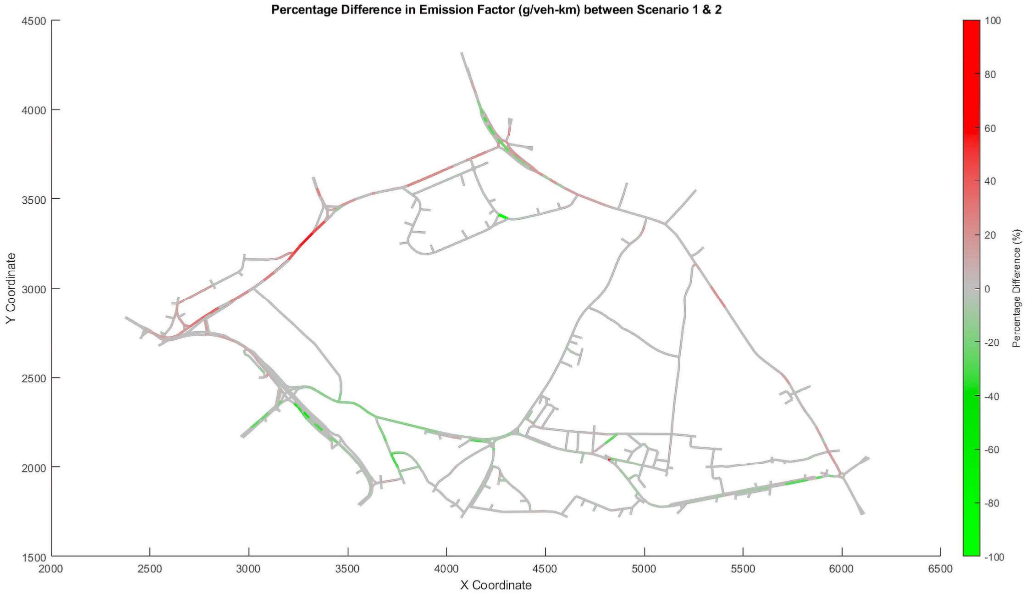
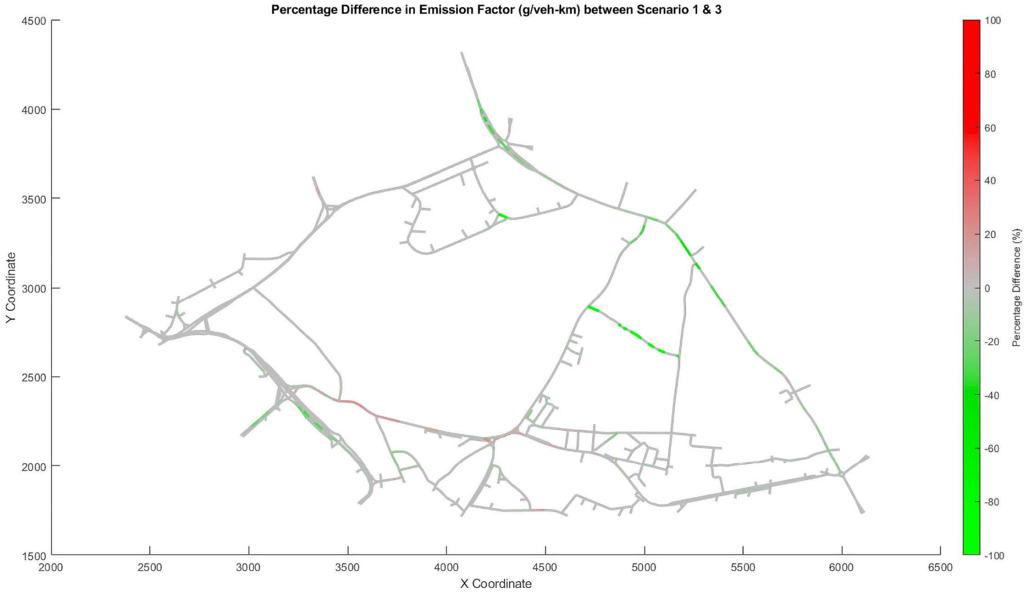
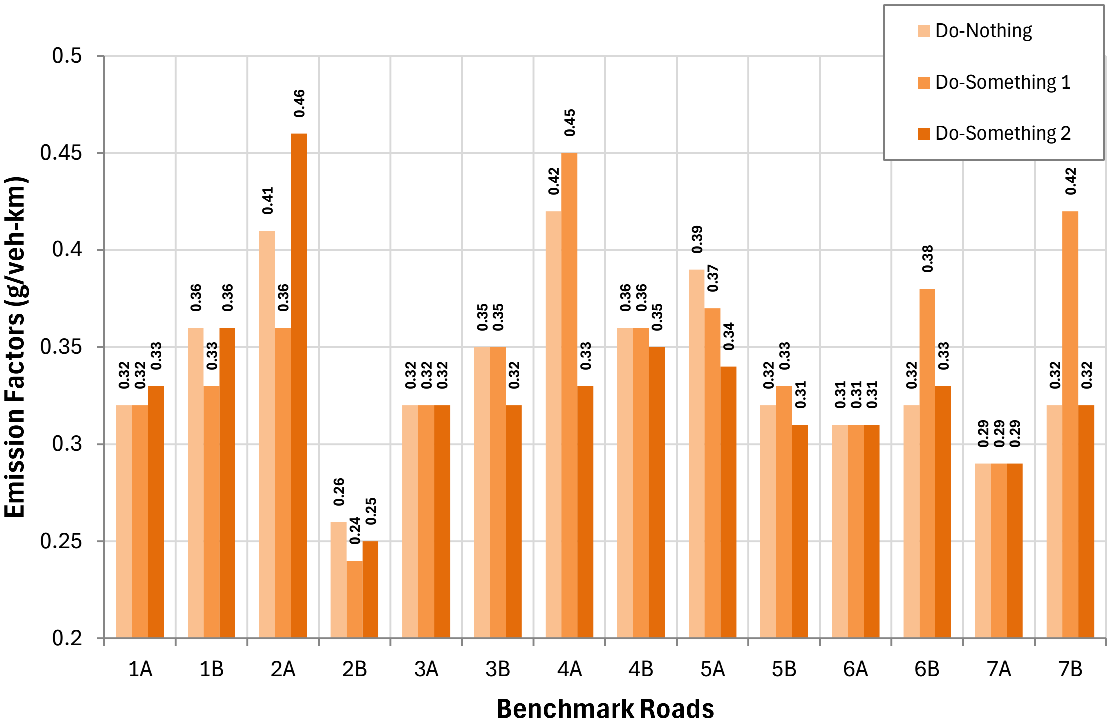


Figure 42. Heatmap showing the percentage difference in EFs between Scenarios 1 & 3



Emission factors between the three scenarios were also compared for the benchmark roads (refer to Figure 43) with this comparison showing that there were some difference in EFs between modelled scenarios.

Figure 43. Comparison of Emission Factor (g/veh-km) for benchmark roads, for each scenario



After analysing the percentage changes across the entire network between scenarios 1 and 2, and scenarios 1 and 3, different patterns of change can be observed between the input (average speed and traffic volume) and output (EFs and pollutant load) parameters, summarised in Figure 44 and Table 11. This data shows that both pollutant load and traffic volume experienced substantial average declines from Scenario 1 to Scenario 2, with relatively smaller changes to Scenario 3, with these changes showing a strong correlation between the two parameters. Emission Factors (EF) and average speed show minor average changes in comparisons between scenarios 1 and 2, and scenarios 1 and 3.

These patterns suggest that changes between scenarios are substantial in many cases, particularly between Scenario 1 and Scenario 2 for pollutant load and traffic volume, indicating significant changes in traffic volume have a great effect on emitted pollutant load. The variability in average speed and EFs is less pronounced, since, especially for EFs, these mostly depend on composition of the vehicle fleet, which remain constant throughout the scenarios.

Figure 44. Comparison of percentage difference between Scenario 1 & 2, and Scenarios 1 & 3

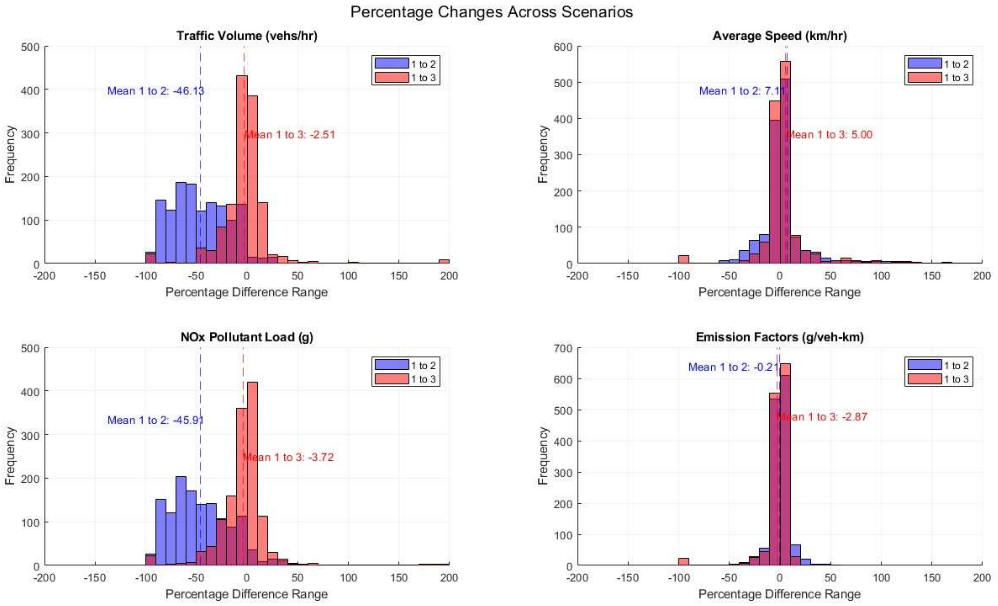


Table 11. Comparison of percentage difference between Scenario 1 & 2, and Scenarios 1 & 3

Inputs and Outputs	**Average Percentage Difference between Scenarios 1 & 2**	**Average Percentage Difference between Scenarios 1 & 3**
Traffic Volume	-46.13%	-2.51%
Average Speed	7.11%	5.00%
Pollutant Load	-45.91%	-3.72%
Emission Factors	-0.21%	-2.87%

4.4. Dispersion Modelling Results

4.4.1. Overview

As discussed in section 2.2 (p.g.5), a main indicator used to express air quality performance is the concentration/presence of a particular pollutant within a cubic metre of air, with air pollution limits being measured micrograms per cubic metre (µg/m^3). Therefore, while the outputs gathered from the emissions model (pollutant loads and emission factors) do themselves imply certain conclusions, their use during the dispersion modelling process contributed to further understanding on the spread of emissions. This section documents the use of this emissions data, along with traffic and meteorological data, and the extracted results from the model for each of the three scenarios, including analysis on the observed changes.

4.4.2. Dispersion Modelling Inputs and Outputs

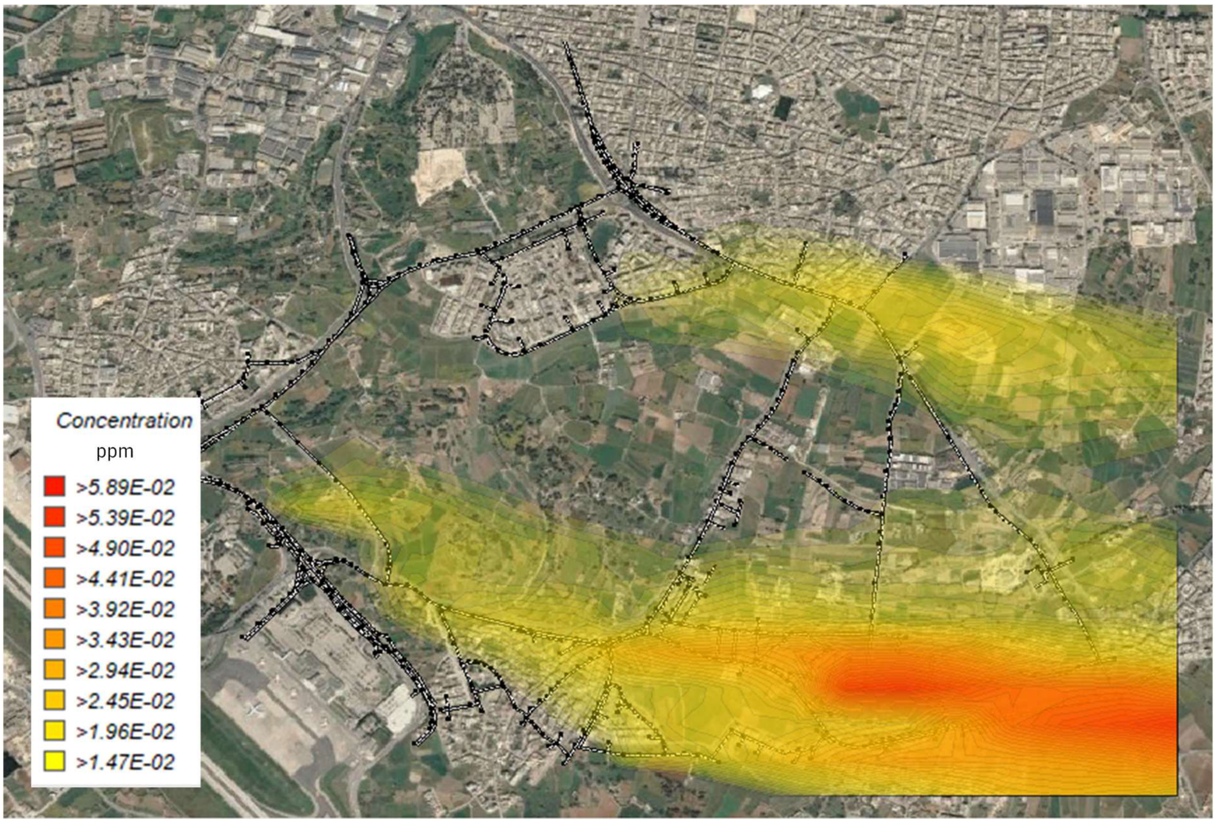
After the calibration of the model (specified in section 3.6, p.g.35), the non-traffic input parameters were kept constant during the simulation of the three modelled scenarios. These non-traffic parameters are documented in Table 12. This was required so that the unique traffic parameters associated with each modelled scenario would be the only changes implemented.

Table 12. Specified non-traffic inputs used during simulations of scenarios

Category	Parameter	Value	Unit
Air Quality Parameters	O_3	0.02	ppm
Air Quality Parameters	NO	0.02	ppm
Air Quality Parameters	Background NO_2	13.65	µg/m^3
Meteorological Data	Wind speed	4.5	m/s
Meteorological Data	Wind Direction	280	degrees
Meteorological Data	Stability Class	D	/
Meteorological Data	Mixing Height	1000	metres
Meteorological Data	Wind Direction (Std. dev)	5	Degrees
Meteorological Data	Temperature	20.2	°C

The dispersion model made use of this data to produce levels of concentrations for the specified pollutant. Specifically, the modelling software was able to generate values of NO_2 concentration levels for each receptor forming part of the receptor grid (mentioned in section 3.6.3, p.g.35). Subsequently, the model also generated contour maps of concentration levels, allowing the visualisation of the spread of pollutants after being emitted. Figure 45 shows a contour map produced for the pollutant spread with traffic inputs of Scenario 1, and the non-traffic inputs specified in Table 12. It has to be noted that the software produced identical contour maps for the other two scenarios, hence only one map is being shown.

Figure 45. Contour NO_2 pollutant concentration map generated by BREEZE Roads



4.4.3. Comparing and Analysing Dispersion Results

The results shows that the application of Measure 1 and Measure 2 (defined in section 3.3.2, p.g.24), represented by scenarios 'Do-Something 1' and 'Do-Something 2' respectively, has minimal impact on the pollutant concentration. Keeping track of the same four real-world concertation collection spots through their modelled counterparts, it can be noted that results do not change much, even showing that the level of NO_2 concentrations increasing slightly overall. Table 13 shows the readings from the benchmark receptors, these being the four receptors closest to the effected site (as referenced in section 3.6.4).

Table 13. Comparison of NO_2 concentration values for receptors across modelled scenarios

Benchmark Receptors	Model Receptor ID	Do-Nothing (μg/m³)	Do-Something 1 (μg/m³)	Do-Something 2 (μg/m³)
GXQ1	3399	47.65	47.95	47.95
GXQ2	3137	46.95	47.05	47.15
	3190	46.45	46.45	46.45
GDJ1	1761	27.55	27.75	27.75
	1708	26.55	26.55	26.75
GDJ2	1546	20.32	20.50	20.48
	1494	22.27	22.43	22.44

4.5. Discussion

Rerouting traffic away from an urban centre to peripheral roads, as proposed in Measure 1, proved ineffective at improving air quality within the intended area. This is primarily due to the area's size and landscape characteristics. Although the study area is larger than one locality, the relative scale and density of the road network do not support traffic deviation as an effective air quality improvement measure. Additionally, the typically flat landscape and low-lying, regular urban development tend to not obstruct air movement. This contrasts with denser and more irregular environments that tend to disrupt the transport of emissions. (Wang et al., 2019). Consequently, shifting traffic, and its associated emissions, to another part of the network away from the centre of Ħal Għaxaq still allowed these emissions to be carried unimpeded back towards the same centre.

Another factor contributing to the minimal change in air quality is the small reduction in the overall quantity of emissions produced. This reduction, documented as pollutant load (in grams) in the previous sections, was minor. Even where there was a reduction in pollutant load emitted into the atmosphere, it was insignificant. In the broader context and compared to the large mixing space that acts as a massive sink, these minor changes in emissions do not register significantly. This is because meteorological actions, which mix and transport these emissions, disperse them too widely for the small reductions to have a noticeable impact (Bogacki et al., 2020; El-Hansali et al., 2021).

CHAPTER 5 - CONCLUSION

5.1. Overview

This dissertation focuses on the application of traffic limiting measures as a primary strategy for mitigating traffic emissions. Recognising the prevalent practice of 'policy transfer', where city authorities and national governments adopt measures from other contexts without adequate testing, this research aims to evaluate how such policies affect traffic behaviour and air quality. Specifically, it seeks to study the effectiveness of traffic limiting measures using metrics related to traffic congestion and air quality.

The central research question guiding this study is: ‘How can digital modelling tools, particularly traffic microsimulation, emission, and air dispersion models, be used to develop a framework for assessing the effectiveness of traffic control measures and policies in reducing traffic generated emissions?’ To answer this question, the study followed a detailed procedure, outlined in section 1.3.1 (p.g.3), and executed in Chapter 4.

The study area was chosen to introduce a potential traffic limiting measure and was backed by sufficient data on traffic, emissions, and other relevant factors. The experimental scenarios were based on changes applied to the real-world scenario, which was based off data captured in October 2023. Ideally, these models would have been used to test for future changes, including changes in traffic volume over time, and possibly even changes in the composition of the vehicle fleet (with zero emission vehicles expected to make up a larger percentage).

The primary metrics used for assessing changes between modelled scenarios included traffic volume, average speed, pollutant load and pollutant concentrations. In terms of air quality, NO_2 was the only pollutant considered in this study given time constraints (explained in section 3.1, p.g.19).

Pollutant concentrations results were the ultimate metric of assessment, showing how emitted pollutants from vehicle exhausts disperse in the environment. The decision to study concentrations was guided by air quality standards that EU member states must adhere to. For NO_2 concentrations specifically, levels must not exceed the limit of $40\mu g/m^3$, with this limit set to get even stricter by 2030 ($20\mu g/m^3$) (referenced in section 2.2.1, p.g.5). Moreover, progress towards studying the implementation of a LEZ in Malta (mentioned in section 2.3.4.5, 14) underscores the relevance of this research.

5.2. Key Findings

The traffic modelling results indicate some improvements from the current scenario (Scenario 1) after introducing the traffic limiting measures (Scenario 2 and Scenario 3). Specifically, for Scenario 2, there was an improvement in traffic performance in the area affected by the traffic limiting policy (within Ħal Għaxaq). However, this improvement was offset by noticeable degradation of the traffic situation on surrounding roads. In contrast, Scenario 3 showed a minimal, yet evident, improvement across most of the road network. This outcome was expected given the reduction in total trips modelled, simulating the carpooling proposal.

The emission model results highlight a measurable difference in the amount of NOx pollutant (in grams) released in the three tested scenarios. However, once this emissions data was inserted into the dispersion modelling software, which also accounts for meteorological aspects, the differences between the three scenarios become less obvious. The dispersion modelling results revealed that, following the implementation of traffic limiting measures, some places (receptors) experienced negligible change in air quality.

This implies that, despite some traffic-related improvements observed after the implementation of the traffic limiting measures, air quality in those places did not see similar improvements. The impact of weather and meteorology on air quality is significant and can influence the outcomes of such measures. Thus, while traffic measures might reduce emissions in certain areas, overall air quality improvements are not guaranteed and can vary depending on local meteorological conditions and the scale of the measure implemented.

Nevertheless, these findings still demonstrate the utility of the modelling process outlined in this research, as it was shown that to effectively target traffic-related emissions in the Maltese context, the strategy's scale must be larger and more extensive.

Still, while it may seem that the one of the more viable solutions is the transition to electric vehicles or zero-emission vehicles, one has to remember that these vehicles still have their issues. Namely:

- Their adoption would merely displace emissions from the road to power generation sources (unless they are renewable)
- They would still contribute to other forms of urban emissions (resuspension of dust and tyre/brake wear), which were not specifically analysed in this research
- They would maintain the other issues associated with private-vehicle use (congestion, pedestrian safety and inefficient use of space).

Moreover, the measure modelled in Scenario 2 (Measure 1 – described in section 3.4.6.1, p.g.30), still has other benefits. Namely, the reduction in traffic resulting from the implemented measures could provide an opportunity to reorganise the streetscape, with potential changes including:

- Developing dedicated cycling lanes and pedestrian walkways to promote active travel.
- Increasing the frequency and coverage of public transport services to offer a viable alternative to private car use.

- Implementing traffic calming measures to improve safety and reduce vehicle speeds.

5.3. Limitations

The accuracy of traffic modelling data could potentially be improved with more precise and extensive data collection. Due to constraints in time and resources, the data collected was not as comprehensive as ideally required, which may have impacted the calibration and validation of the traffic model against real-world conditions.

A key consideration in generating traffic models is the resolution or level of detail of the network under study. In this study, the level of detail was constrained by available resources, which may have impacted the precision of the models.

The potential of integrating a traffic-emission air quality modelling toolset was not entirely realised due to early stages of familiarity with the software and limited real-world data. Ideally, second-by-second traffic data would better represent stop-and-go traffic. However, low-resolution pollutant data restricted real-time analysis, leading to averaged parameters (like speed and volume), which could misrepresent the real-world situation.

The modelling process required the integration of three separate tools, each needing its own calibration. Late in the research stage, integrated tools were found that could combine some tasks, particularly between traffic and emissions modelling. Given more time, the use of such tools could have been implemented, potentially reducing the need for calibration and data exchange between different software systems.

Discrepancies between dispersion model outputs and local air quality measurements can occur due to uncertainties in traffic flow estimates, vehicle emissions, background concentration levels, meteorological data, and model limitations, particularly regarding topography.

5.4. Recommendations

Throughout the development of the modelling process outlined in this research, several important areas of note were identified. The following recommendations are being proposed and may be considered useful when conducting assessments of traffic-emission reduction strategies.

1 Improved Data Collection – Gathering more detailed and accurate traffic and pollutant data, ideally on an hourly or real-time basis, will provide higher resolution data for modelling. This approach ensures that models are based on robust and precise information, rather than assumptions.

2 Use of Comprehensive Microsimulation Traffic Models – These tools are more effective at predicting changes in traffic behaviour following network changes compared to

smaller intersection models. Modelling a larger area of the road network offers better insight into how a smaller change may impact the surrounding network. This is crucial for determining air quality because, as noted in the results, the performance of the surrounding network is as important as the performance of the small network change in determining air quality.

3 Improved Emissions Modelling – Emission models, such as the one employed in this research, can better bridge the gap between traffic model outputs and dispersion model inputs. This was demonstrated during this study when traffic modelling activity data was used instead of mean activity data (mentioned in section 3.5.2, p.g.32).

4 Policy Testing – Policies should be tested in a digital environment before implementation to identify potential unintended consequences. Iterative testing and refinement can help optimise policy measures, ensuring they achieve the desired outcomes without adverse effects.

5.5. Future Research

The following are several ideas for future research that can be conducted to improve and add to the research presented in this dissertation.

1 Additional Policies and Measures for Testing – Future research should consider testing other traffic and emission reduction policies, including the task of defining how these policies may impact traffic demand (as outlined in section 3.3.2, p.g.24), and, ultimately, how these may affect air quality. These could include:

- Enhancement of public transportation infrastructure to reduce dependency on private vehicles.
- Introduction of low-emission zones (LEZ) with stricter entry criteria for older, high-emission vehicles.
- Promotion of active mobility options such as cycling and walking through dedicated lanes and pedestrian zones.
- Carpooling measures that are more widespread than the one tested in this study.
- A combination of several policies.

2 Vehicle Fleet Composition – In this study, the vehicle fleet composition was kept constant, as it stood when this study was conducted. Future research should explore modifying the composition of the vehicle fleet to study the impact of increasing the proportion of zero-emission vehicles on air quality. This could involve:

- Modelling different scenarios to determine the percentage of zero-emission vehicles required to meet the updated NO_2 concentration limit of 20μg/m^3 planned to be introduced in 2030.
- Evaluating the rate of zero-emission vehicle adoption in Malta and assessing whether additional measures are necessary to achieve the air quality targets.

3 Sensitivity Analysis for Dispersion Modelling – To further refine the accuracy of the dispersion model, sensitivity analysis could be conducted for non-traffic inputs. By varying key inputs (such as mixing height, wind direction, and wind speed) and observing their effects on concentration results, it would be possible to determine which non-traffic input has the most significant impact. This could be done by incrementally adjusting each input (e.g., varying wind direction by 30 degrees at a time) while keeping the others constant, providing a clearer understanding of the factors influencing air quality outcomes.

5.6. Summary of Contributions

During this research process, several outcomes have been identified. Firstly, the use of the documented modelling approach demonstrates the effectiveness of evaluating the impact of traffic limiting measures on air quality. This is achieved through a combination of microsimulation traffic modelling, emission modelling, and air dispersion modelling. The study's focus on modelling a larger area, rather than just the immediate vicinity of a network change, underscores the importance of considering the surrounding road network to capture the full impact of traffic measures.

Secondly, the research underscores the importance of having a robust framework for evaluating the environmental impact of traffic policies, which has not been previously applied to traffic-limiting measures in Malta. This framework could potentially serve as a valuable tool for policymakers and urban planners seeking to understand and mitigate the environmental consequences of traffic management strategies in specific contexts.

Thirdly, the study highlights the importance of comprehensive testing and the potential for unexpected outcomes. This is especially the case when there is an expectation that certain results would be achieved, but through testing, the hypothesis is proven wrong. Specifically, the results of the two experimental scenarios modelled, which disproved the expected outcome, provide insight that a more holistic approach is necessary when addressing traffic and air quality issues, particularly given the scale and density of the Maltese road network.

APPENDIX A - TRAFFIC MODELLING

A.1. Building the Traffic Model

A.1.1. Constructing the Base Network

In Paramics Discovery™, the construction of the base road network involves the use of nodes and links. Nodes represent the start or end point of a link, or its connection to another link. This enables the definition of road alignments, widths, number of lanes, curvature, and gradient.

The connection between several links, or a junction, can be modelled to replicate the real-world configuration, including minor stop-sign junctions, roundabouts, signalised junctions, and multi-level interchanges.

Most junctions are the simple intersection between two minor roads, which only required the identification of priority rules like give-way or stop signs. For roundabouts, junction rules had to be modified to emulate real-world movements, particularly when instructing vehicles which approach lanes and lanes within the roundabout to use. In the case of signalised junctions, traffic-light timings had to be collected to replicate the different phases. Pedestrian crossings were also included where present in the existing network, with timings reflecting the average crossing time for a pedestrian.

A.1.2. Link Categories

Links had to be individually categorised based on several different attributes, including road type, road class, speed limit, and cost factor, with these determining the behaviour of vehicles using the modelled network.

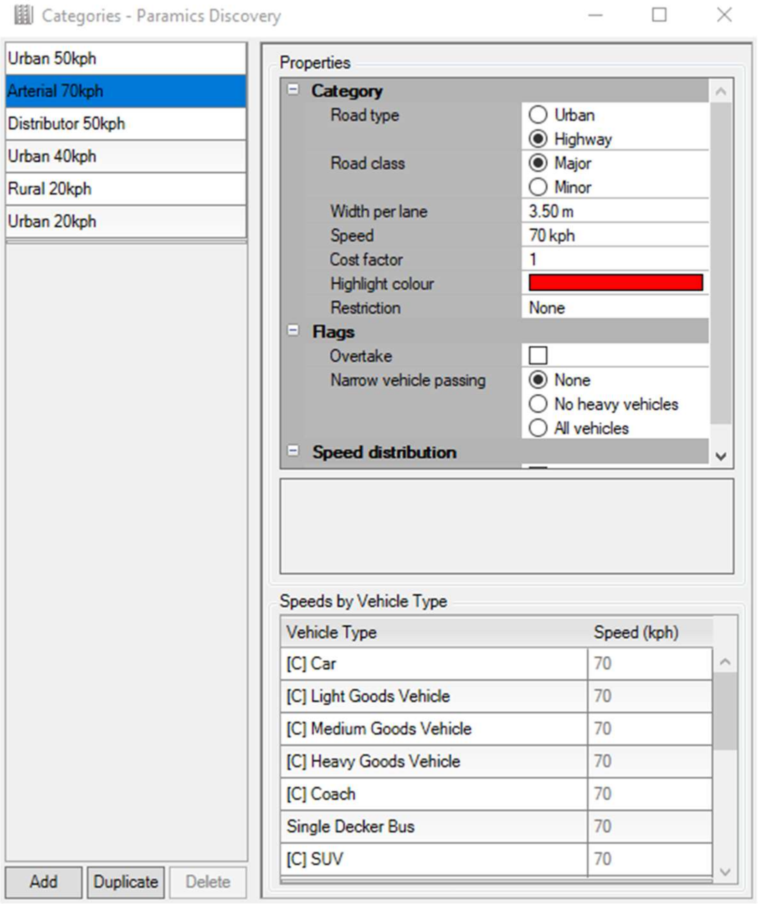
A.1.3. Other Link Properties

There were several parameters that needed further defining, including visibility, gap acceptance and merging properties. These determine how the modelled vehicles interact with each other, especially when crossing paths at junctions. Figure 46 shows how link categories are defined within the software.

A.1.4. Public Transport

Consideration was also given to public transport routes using the study area network. Bus stop locations were defined using public transport maps as reference. The bus routes were defined along the bus stop locations and were given a frequency (Malta Public Transport, 2024). Figure 47 shows an example of bus stops being defined within the model.

Figure 46. Link Categories as defined within Paramics Discovery



- Urban 50kph
- Arterial 70kph
- Distributor 50kph
- Urban 40kph
- Rural 20kph
- Urban 20kph

Properties

Category

Road type: ○ Urban ● Highway
Road class: ● Major ○ Minor
Width per lane: 3.50 m
Speed: 70 kph
Cost factor: 1
Highlight colour: 🟥
Restriction: None

Flags

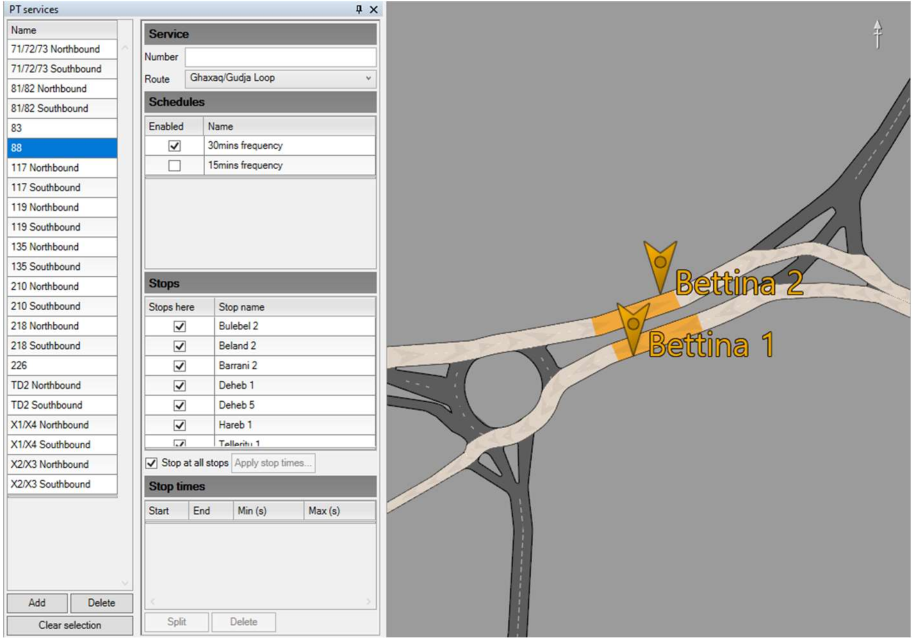
Overtake: ☐
Narrow vehicle passing: ● None ○ No heavy vehicles ○ All vehicles

Speed distribution

Speeds by Vehicle Type

Vehicle Type	Speed (kph)
[C] Car	70
[C] Light Goods Vehicle	70
[C] Medium Goods Vehicle	70
[C] Heavy Goods Vehicle	70
[C] Coach	70
Single Decker Bus	70
[C] SUV	70

Figure 47. Bus Routes as defined within Paramics Discovery



Name
71/72/73 Northbound
71/72/73 Southbound
81/82 Northbound
81/82 Southbound
83
88
117 Northbound
117 Southbound
119 Northbound
119 Southbound
135 Northbound
135 Southbound
210 Northbound
210 Southbound
218 Northbound
218 Southbound
226
TD2 Northbound
TD2 Southbound
X1/X4 Northbound
X1/X4 Southbound
X2/X3 Northbound
X2/X3 Southbound

Service

Number:
Route: Ghaxaq/Gudja Loop

Schedules

Enabled	Name
☑	30mins frequency
☐	15mins frequency

Stops

Stops here	Stop name
☑	Bulebel 2
☑	Beland 2
☑	Barrani 2
☑	Deheb 1
☑	Deheb 5
☑	Hareb 1

☑ Stop at all stops

Stop times

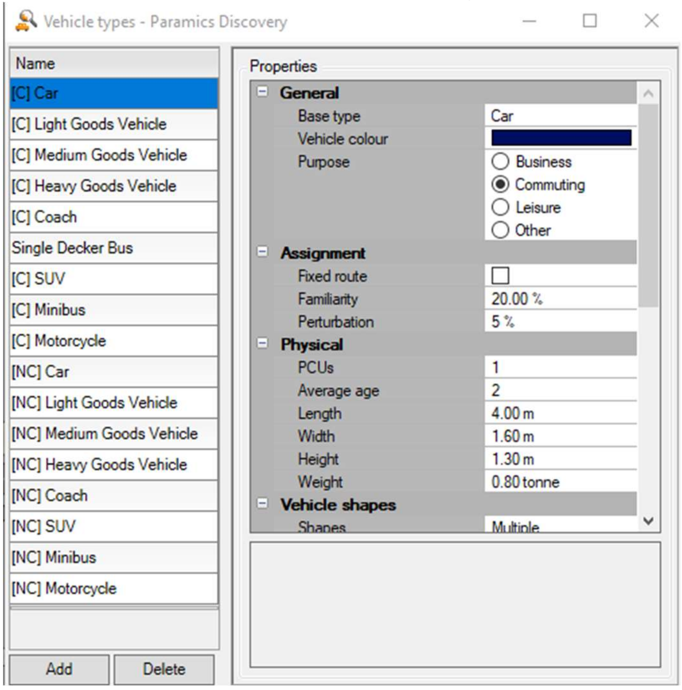
Start	End	Min (s)	Max (s)

A.1.5. Vehicle Types and Parameters

Traffic modelling requires that different types of vehicles be defined to reflect the composition of vehicles using the road network, these having a great effect on results. In this case, national fleet composition statistics were used (NSO, 2023a). There are eight vehicle types represented in the model, categorised into two main types, as indicated in Table 14. Each vehicle type has its individual parameters that can be tweaked or left as default, namely maximum speed, acceleration/deceleration rate and size.

Vehicle types can also be edited with regards to routing behaviour, with the main routing parameters being Familiarity and Perturbation, these affecting the routing behaviour of these vehicles.

Figure 48. Vehicle Types as defined within Paramics Discovery



Name
[C] Car
[C] Light Goods Vehicle
[C] Medium Goods Vehicle
[C] Heavy Goods Vehicle
[C] Coach
Single Decker Bus
[C] SUV
[C] Minibus
[C] Motorcycle
[NC] Car
[NC] Light Goods Vehicle
[NC] Medium Goods Vehicle
[NC] Heavy Goods Vehicle
[NC] Coach
[NC] SUV
[NC] Minibus
[NC] Motorcycle

Properties

General
Base type: Car
Vehicle colour
Purpose: ○ Business ● Commuting ○ Leisure ○ Other

Assignment
Fixed route: ☐
Familiarity: 20.00 %
Perturbation: 5 %

Physical
PCUs: 1
Average age: 2
Length: 4.00 m
Width: 1.60 m
Height: 1.30 m
Weight: 0.80 tonne

Vehicle shapes
Shapes: Multiple

Table 14. Vehicle categories & types defined in the model (NSO, 2023a)

Vehicle Types		Percentage of Fleet	
Light Vehicles	Cars	65.5%	100%
	Motorcycles	9.2%	
	SUVs	14.7%	
	LGVs	10.2%	
	Minibus	0.4%	
Heavy Vehicles	Coach	2.3%	100%
	MGVs	72.7%	
	HGVs	25.1%	

A.1.6. Defining Zones within the Traffic Model

Another step in this process was the dissection of the study area into several zones within the simulation. Zones act as both origin and destination for vehicles within the model, meaning they are used to control the input and output of vehicles within the network, with vehicles taking the least cost route. These zones then form a network trip matrix composed of the number of vehicles originating from and going to each zone. Zone portals are used to further control the release and intake of vehicles for zones with multiple access portals.

The study area model made use of 41 zones. Some of the zones were used to simulate the entry/exit points outside the modelled area, while others were used to simulate locations within the model that act as origins/destinations for vehicular traffic. For simplification, 33 zones are shown in Figure 49, with the outside entrance and exit zones being considered as one zone.

Figure 49. The modelled road network and numbered zones within Paramics Discovery

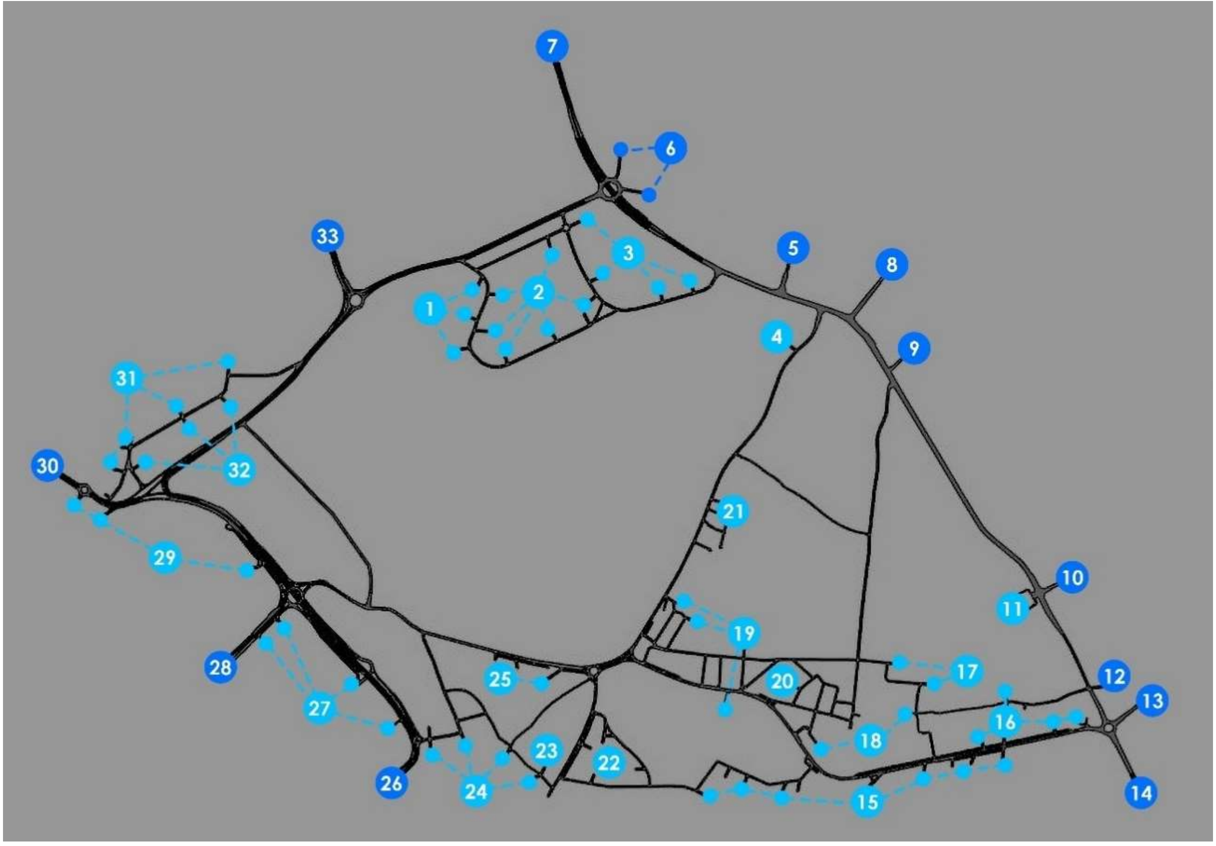


Table 15. Zones represented within the traffic model

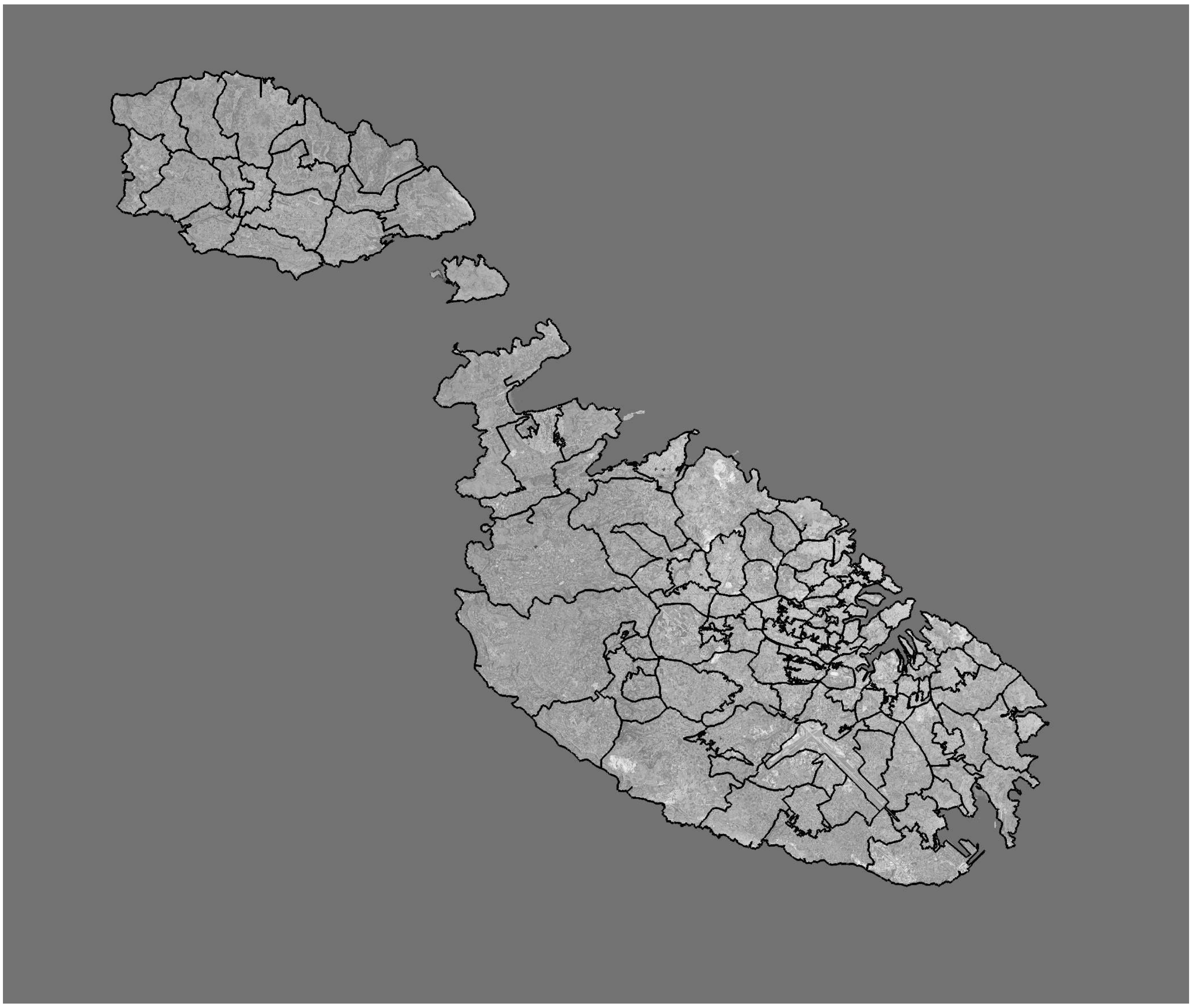
Zone Number	Area	Connection Type
1	Santa Luċija	Inside
2	Santa Luċija	Inside
3	Santa Luċija	Inside
4	Santa Luċija	Inside
5	Triq il-Palma	Outside
6	Ħal Tarxien	Outside
7	Vjal Santa Luċija	Outside
8	Triq San Anard	Outside
9	Triq tal-Ħotba	Outside
10	Vjal il-25 ta' Novembru	Outside
11	LIDL, Ħal Għaxaq	Inside
12	Triq il-Labour	Outside
13	Triq il-President Anton Buttiġieġ	Outside
14	Triq Għar Dalam	Outside
15	Ħal Għaxaq	Inside
16	Ħal Għaxaq	Inside
17	Ħal Għaxaq	Inside
18	Ħal Għaxaq	Inside
19	Ħal Għaxaq	Inside
20	Ħal Għaxaq	Inside
21	Ħal Għaxaq	Inside
22	Il-Gudja	Inside
23	Il-Gudja	Inside
24	Il-Gudja	Inside
25	Il-Gudja	Inside
26	Triq Ħal Far	Outside
27	Malta International Airport	Inside
28	Kirkop Tunnels	Outside
29	Ħal Luqa	Inside
30	Triq San Tumas	Outside
31	Ħal Luqa	Inside
32	Ħal Luqa	Inside
33	Triq Giuseppe Garibaldi	Outside

A.2. Prior Matrix

A.2.1. Macroscopic Traffic Model Data Processing

The process of defining a pattern/prior matrix is aided by having a large-scale/macroscopic traffic model of the region required. In the case for Malta, the National Transport Model (NTM) is a country-wide, trip origin-destination matrix that outlines traffic demand estimations of trip volumes between different zones throughout the country. These zones are called Traffic Analysis Zones (TAZs), with each TAZ referring to a locality, part of a locality, or another distinct activity area (refer to Figure 50).

Figure 50. Map of Traffic Analysis Zones (TAZs) (Transport Malta, 2023)



There are a total of 136 distinct TAZs considered by the NTM, 119 TAZs referring to localities (listed in Figure 51) and 17 referring to industrial estates (listed in Figure 52), with each TAZ having an associated zone number.

Figure 51. Reference between TAZs and Localities (Transport Malta, 2023)

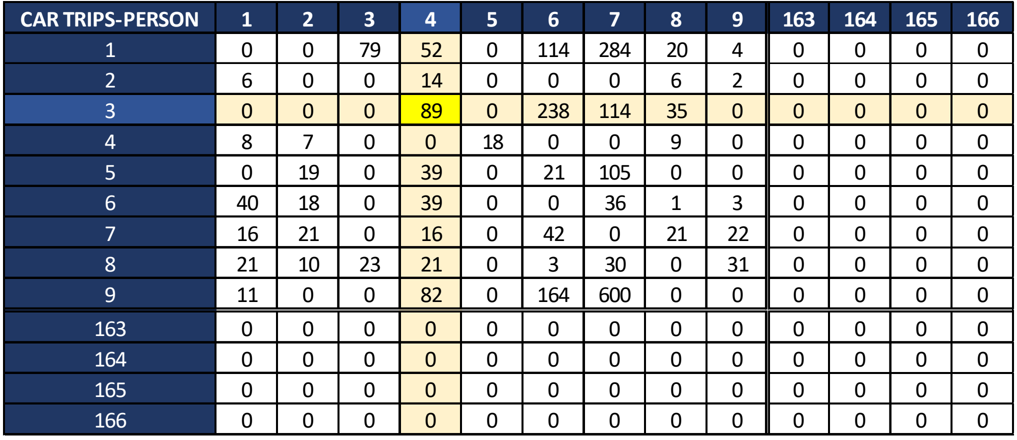
ZONE	LOCALITY	ZONE	LOCALITY	ZONE	LOCALITY	ZONE	LOCALITY
1	L-Gharb	31	L-Imtarfa/Mdina	61	Ta' Xbiex	92	Haz-Zabbar
2	L-Ghasri	32	L-Imtarfa/Mdina	62	Il-Gzira	93	Haz-Zabbar
3	Iz-Zebbug	33	Il-Mosta	63	Il-Gzira	94	Hal Tarxien
4	San Lawrenz	34	Il-Mosta	64	Had-Dingli	95	Hal Tarxien
5	Ta' Kercem	35	Il-Mosta	65	Santa Venera	96	Santa Lucija
6	Ir-Rabat, Ghawdex	36	Hal Gharghur	66	Santa Venera	97	Is-Siggiewi
7	Ir-Rabat, Ghawdex	37	Is-Swieqi	67	Tal-Pieta'	98	Is-Siggiewi
8	Il-Fontana	38	Is-Swieqi	68	Il-Hamrun	99	L-Imqabba
9	Ix-Xaghra	39	Pembroke	69	Il-Hamrun	100	Hal Kirkop
10	Ix-Xaghra	40	H'Attard	70	Il-Hamrun	101	Hal Safi
11	In-Nadur	41	H'Attard	71	Il-Furjana	102	Il-Qrendi
12	In-Nadur	42	H'Attard	73	Valletta	103	Hal Luqa
13	Il-Munxar	43	Hal Lija	74	Il-Kalkara	104	Hal Luqa
14	Ta' Sannat	44	L-Iklin	75	Birgu	105	Il-Gudja
15	Ix-Xewkija	45	San Gwann	76	L-Isla	106	Hal Ghaxaq
16	Ghajnsielem	46	San Gwann	77	Bormla	107	Iz-Zurrieq
17	Comino	47	San Gwann	78	Bormla	108	Iz-Zurrieq
18	Il-Qala	48	San Giljan	79	Ix-Xghajra	109	Birzebbuga
19	Il-Mellieha	49	San Giljan	80	Haz-Zebbug	110	Birzebbuga
20	Il-Mellieha	50	Il-Gzira	81	Haz-Zebbug	111	Birzebbuga
21	Il-Mellieha	51	Tas-Sliema	82	Hal Qormi	112	Marsaxlokk
22	L-Imgarr	52	Tas-Sliema	83	Hal Qormi	113	Marsaxlokk
23	San Pawl il-Bahar	53	Tas-Sliema	84	Hal Qormi	114	Iz-Zejtun
24	San Pawl il-Bahar	54	Hal Balzan	85	Il-Marsa	115	Iz-Zejtun
25	San Pawl il-Bahar	55	Birkirkara	86	Il-Marsa	116	Iz-Zejtun
26	In-Naxxar	56	Birkirkara	87	Paola	117	Marsaskala
27	In-Naxxar	57	Birkirkara	88	Paola	118	Marsaskala
28	Ir-Rabat	58	Birkirkara	89	Il-Fgura	119	Marsaskala
29	Ir-Rabat	59	L-Imsida	90	Il-Fgura	120	MIA (Airport)
30	Ir-Rabat	60	L-Imsida	91	Il-Fgura		

Figure 52. Reference between TAZs and Industrial Estates

TAZ	LOCALITY	INDUSTRIAL ESTATE
150	Iz-Zejtun	Bulebel
151	Il-Marsa	Deep Water Quay
152	Birzebbuga	Free Port
153	Birzebbuga	Hal Far
154	Paola	Kordin
155	Hal Luqa	Airport
156	Il-Marsa	Marsa
157	San Gwann	San Gwann
158	In-Naxxar	Maghtab Quarry
159	In-Naxxar	Naxxar Quarry
160	L-Imqabba	Thomson
161	Marsaxlokk	Delimara
162	Bormla	Dockyards
163	Il-Marsa	Albert Town / Enemalta
164	Birkirkara	Mriehel
165	Hal Qormi	Handaq
166	H'Attard	Nectar

Figure 53 shows a sample of the origin-destination matrix for car trips during the morning peak hour, with the rows indicating the zones of origin, and the columns indicating the destination zones. For example, there were 89 cars originating from zone 3 that have their destination in zone 4. It is important to note that there were around 70,000 trips recorded in this NTM data.

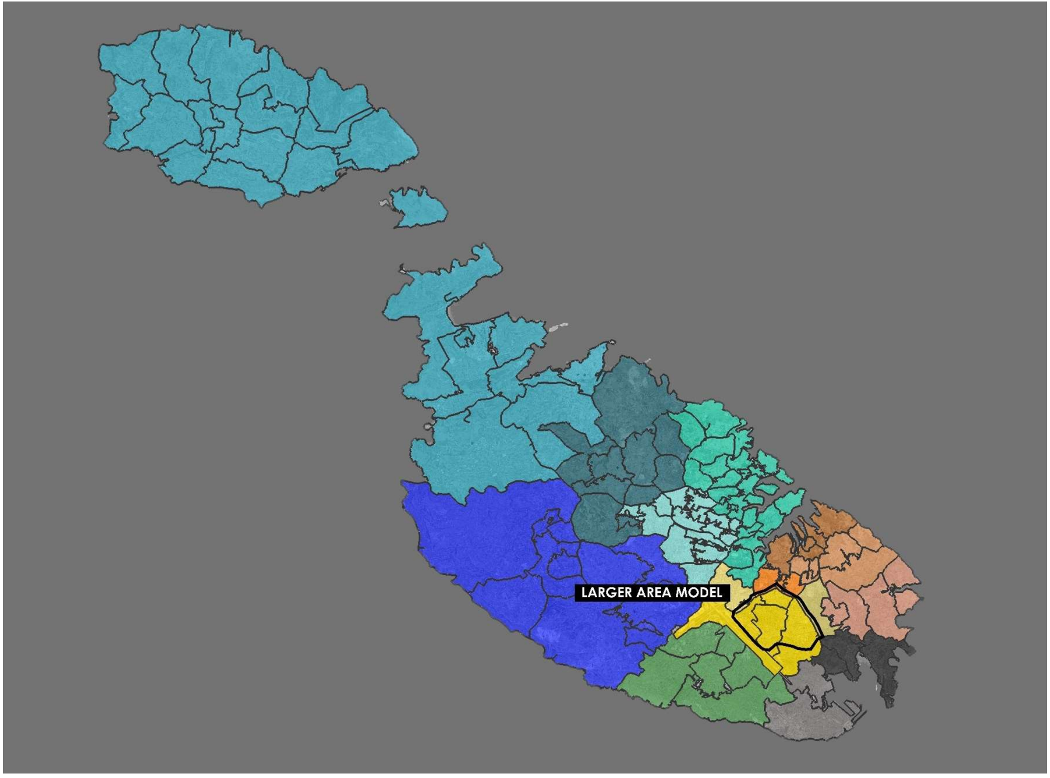
Figure 53. A sample of the NTM generated origin-destination matrix (Transport Malta, 2023)



CAR TRIPS-PERSON	1	2	3	4	5	6	7	8	9	163	164	165	166
1	0	0	79	52	0	114	284	20	4	0	0	0	0
2	6	0	0	14	0	0	0	6	2	0	0	0	0
3	0	0	0	89	0	238	114	35	0	0	0	0	0
4	8	7	0	0	18	0	0	9	0	0	0	0	0
5	0	19	0	39	0	21	105	0	0	0	0	0	0
6	40	18	0	39	0	0	36	1	3	0	0	0	0
7	16	21	0	16	0	42	0	21	22	0	0	0	0
8	21	10	23	21	0	3	30	0	31	0	0	0	0
9	11	0	0	82	0	164	600	0	0	0	0	0	0
163	0	0	0	0	0	0	0	0	0	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0	0	0	0
165	0	0	0	0	0	0	0	0	0	0	0	0	0
166	0	0	0	0	0	0	0	0	0	0	0	0	0

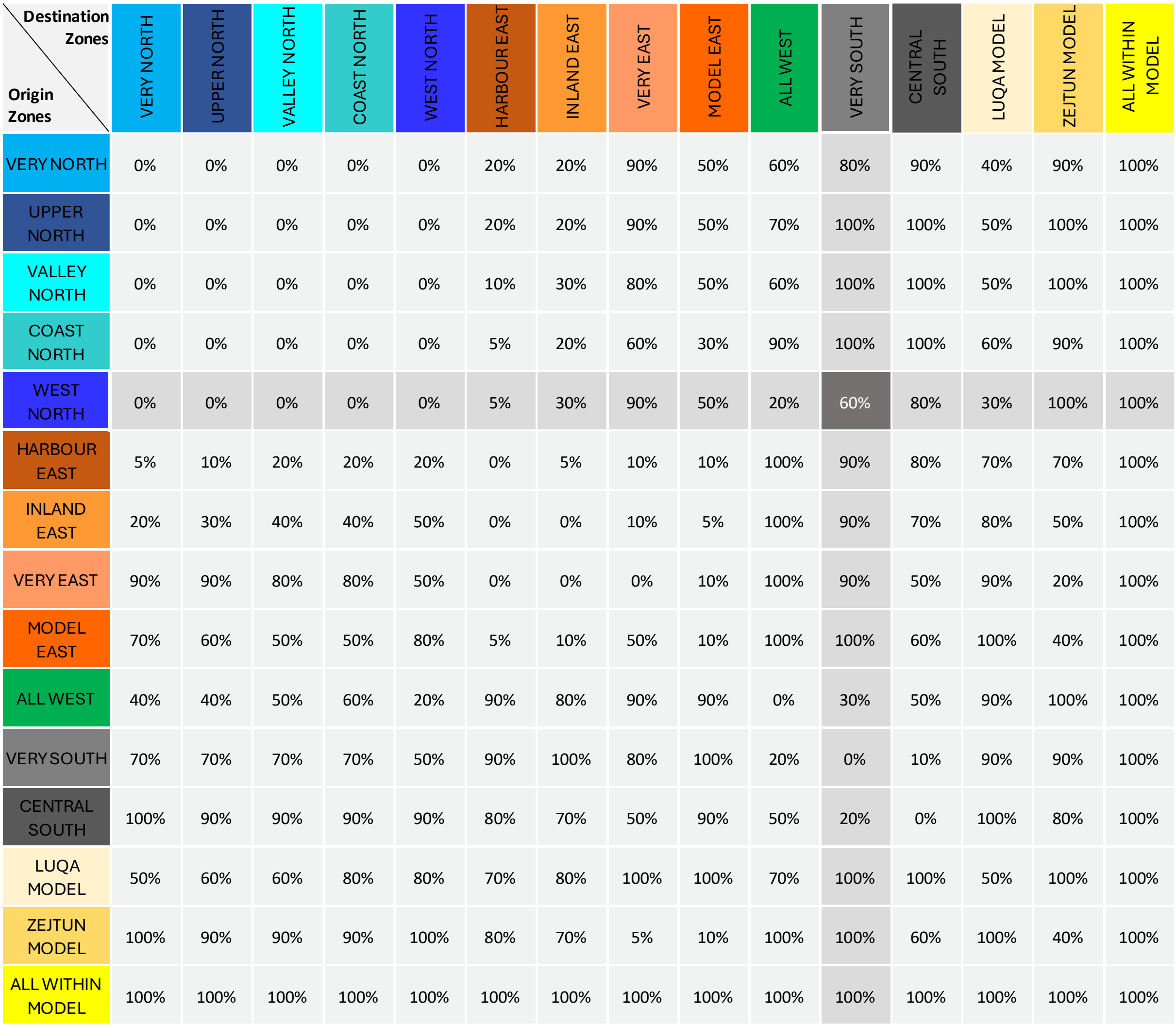
By analysing this macroscopic level data, traffic demand relevant to the study area being considered can be defined (SYSTRA, 2022b). To achieve this, the 136 individual TAZs were simplified and grouped into 15 origin/destination nodes or 'sub-designations', meaning that the amount of processing needed was reduced. This involved combining TAZs based on proximity and perceived similarity in routing for vehicles (shown in Figure 54).

Figure 54. Map of TAZs grouped into 'sub-designations'



Following this, the likelihood of a vehicle passing from the modelled network was determined for each of the 15 sub-designation route pairs, this being informed by route planner tools such as Google Maps, OpenStreetMaps and geographic information system (GIS) software. For example, it was estimated that 60% of all the vehicles starting their journey in ‘West-North’ and ending it in ‘Very-South’ would pass through the modelled network (refer to Figure 55).

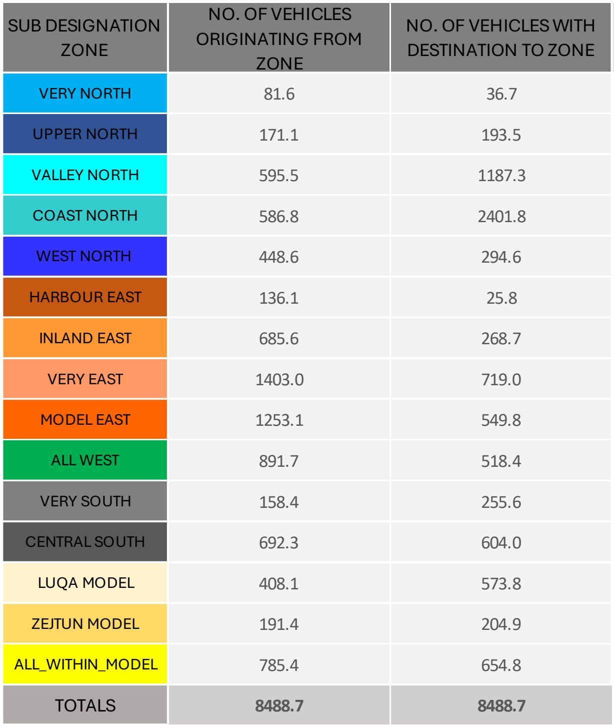
Figure 55. Matrix containing the likelihood of an O-D trip pair passing through the studied network



Destination Zones / Origin Zones	VERY NORTH	UPPER NORTH	VALLEY NORTH	COAST NORTH	WEST NORTH	HARBOUR EAST	INLAND EAST	VERY EAST	MODEL EAST	ALL WEST	VERY SOUTH	CENTRAL SOUTH	LUQA MODEL	ZEJTUN MODEL	ALL WITHIN MODEL
VERY NORTH	0%	0%	0%	0%	0%	20%	20%	90%	50%	60%	80%	90%	40%	90%	100%
UPPER NORTH	0%	0%	0%	0%	0%	20%	20%	90%	50%	70%	100%	100%	50%	100%	100%
VALLEY NORTH	0%	0%	0%	0%	0%	10%	30%	80%	50%	60%	100%	100%	50%	100%	100%
COAST NORTH	0%	0%	0%	0%	0%	5%	20%	60%	30%	90%	100%	100%	60%	90%	100%
WEST NORTH	0%	0%	0%	0%	0%	5%	30%	90%	50%	20%	60%	80%	30%	100%	100%
HARBOUR EAST	5%	10%	20%	20%	20%	0%	5%	10%	10%	100%	90%	80%	70%	70%	100%
INLAND EAST	20%	30%	40%	40%	50%	0%	0%	10%	5%	100%	90%	70%	80%	50%	100%
VERY EAST	90%	90%	80%	80%	50%	0%	0%	0%	10%	100%	90%	50%	90%	20%	100%
MODEL EAST	70%	60%	50%	50%	80%	5%	10%	50%	10%	100%	100%	60%	100%	40%	100%
ALL WEST	40%	40%	50%	60%	20%	90%	80%	90%	90%	0%	30%	50%	90%	100%	100%
VERY SOUTH	70%	70%	70%	70%	50%	90%	100%	80%	100%	20%	0%	10%	90%	90%	100%
CENTRAL SOUTH	100%	90%	90%	90%	90%	80%	70%	50%	90%	50%	20%	0%	100%	80%	100%
LUQA MODEL	50%	60%	60%	80%	80%	70%	80%	100%	100%	70%	100%	100%	50%	100%	100%
ZEJTUN MODEL	100%	90%	90%	90%	100%	80%	70%	5%	10%	100%	100%	60%	100%	40%	100%
ALL WITHIN MODEL	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Subsequently, these percentages were applied to the values of the NTM origin-destination matrix, which outputted the amount of vehicles needed to be represented within the traffic model. Figure 56 shows how many vehicles start and end their journey from each sub-designation, and also shows the total amount of vehicles needed to be modelled. This total value represents around 12% of all trips represented in the NTM data.

Figure 56. Number of vehicles starting and ending their journey from each sub-designation



SUB DESIGNATION ZONE	NO. OF VEHICLES ORIGINATING FROM ZONE	NO. OF VEHICLES WITH DESTINATION TO ZONE
VERY NORTH	81.6	36.7
UPPER NORTH	171.1	193.5
VALLEY NORTH	595.5	1187.3
COAST NORTH	586.8	2401.8
WEST NORTH	448.6	294.6
HARBOUR EAST	136.1	25.8
INLAND EAST	685.6	268.7
VERY EAST	1403.0	719.0
MODEL EAST	1253.1	549.8
ALL WEST	891.7	518.4
VERY SOUTH	158.4	255.6
CENTRAL SOUTH	692.3	604.0
LUQA MODEL	408.1	573.8
ZEJTUN MODEL	191.4	204.9
ALL_WITHIN_MODEL	785.4	654.8
TOTALS	**8488.7**	**8488.7**

A.2.2. Matching Sub-designation Data with Traffic Model Zones

These vehicles had to be assigned to the 41 zones specified within the traffic model (outlined in Appendix A.1.6). This involved seeing how many vehicles should be entering and exiting from each traffic model zone during the simulation.

To find how many vehicles start their journey at the traffic model zones, each origin-destination trip pair (between two sub-designations) was given a percentage chance at originating from each of those zones. As a result, the total number of vehicles originating from each traffic model zone was quantified.

Following this, the total number of vehicles exiting from each traffic model zone were found through determining a vehicle's likely exit zone based on its destination sub-designation. For example, a vehicle travelling to 'Very North' was given a 50% chance of exiting from zone 30, a 20% chance from zone 33, and a 30% chance from zone 7.

By mapping the NTM data onto the zones defined in the traffic model, a prior matrix for traffic demand was established, this being documented in Figure 57.

Figure 57. The origin-destination prior matrix

ORIGIN ZONES	DESTINATION ZONES																																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	106	107	113	114	126	128	130	133
1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	1	2	2	5	8	8
2	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	1	2	2	5	8	8
3	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	1	2	2	5	8	8
4	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	1	2	2	5	8	8
5	1	1	1	0	0	0	0	8	0	8	0	1	0	0	1	1	1	1	1	1	1	2	2	2	2	0	10	0	0	0	1	0	0	4	94	12	2	3	24	79	56
6	2	2	2	1	2	0	0	16	0	17	0	3	0	0	1	1	1	1	1	1	1	2	2	2	2	0	13	0	1	0	1	1	0	8	235	26	5	7	52	179	139
7	7	7	7	2	30	0	0	166	9	103	1	19	0	0	4	4	4	4	4	4	4	8	8	8	8	0	54	0	4	0	11	4	0	124	3	183	154	86	25	8	3
8	7	7	7	2	4	0	0	0	2	17	1	4	0	0	3	3	3	3	3	3	3	8	8	8	8	0	50	0	4	0	9	4	0	16	297	34	39	29	150	199	182
9	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	3	0	0	0	0	0	0	0	0	3	4	1	0	0	0
10	1	1	1	0	2	0	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	4	0	5	0	11	5	0	10	171	5	31	28	15	106	100
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	1	1
12	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	26	0	6	6	2	15	15
13	1	1	1	0	2	0	0	10	1	5	0	2	0	0	0	0	0	0	0	0	0	1	1	1	1	0	6	0	10	0	24	10	0	10	277	21	86	74	30	175	163
14	1	1	1	0	4	0	0	25	2	23	0	5	0	0	0	0	0	0	0	0	0	1	1	1	1	0	4	0	2	0	4	2	0	20	212	43	0	5	22	109	127
15	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	1	5	7	8
16	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	1	5	7	8
17	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	1	5	7	8
18	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	1	5	7	8
19	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	1	5	7	8
20	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	1	5	7	8
21	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	1	5	7	8
22	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2	21	2	2	2	8	12	12
23	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2	21	2	2	2	8	12	12
24	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2	21	2	2	2	8	12	12
25	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2	21	2	2	2	8	12	12
26	1	0	0	0	2	0	0	9	1	8	0	2	0	0	0	0	0	0	0	0	0	1	1	1	1	0	4	0	1	0	2	1	0	8	39	16	12	3	6	21	23
27	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	58	0	1	0	0	68	31
28	10	6	6	1	16	0	0	85	4	45	1	10	0	0	4	4	4	4	4	4	4	8	8	8	8	0	53	0	4	0	77	31	0	64	90	93	27	18	4	132	42
29	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	21	1	1	1	2	20	11
30	6	3	3	1	11	0	0	58	4	34	1	7	0	0	2	2	2	2	2	2	2	5	5	5	5	0	8	0	9	0	110	11	0	45	1	66	80	49	37	66	2
31	0	0	0	0	1	0	0	5	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5	58	4	1	0	0	68	31
32	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	21	1	1	1	2	20	11
33	1	1	1	1	4	0	0	19	1	7	0	1	0	0	1	1	1	1	1	1	1	2	2	2	2	0	11	0	5	0	27	5	0	15	0	13	21	23	11	16	1
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
126	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX B - JUNCTION TURN MOVEMENTS

As mentioned in section 4.2.2 (p.g.42), comparisons of turn movements between the three scenarios have been conducted on three additional junctions, labelled as Junction B, C and D (refer to Figure 58). Each junction is referred to in the following figures and tables

- Junction B – Figure 59 and Table 16
- Junction C – Figure 60 and Table 17
- Junction D – Figure 61 and Table 18

Figure 58. A map showing the location of the junctions being compared

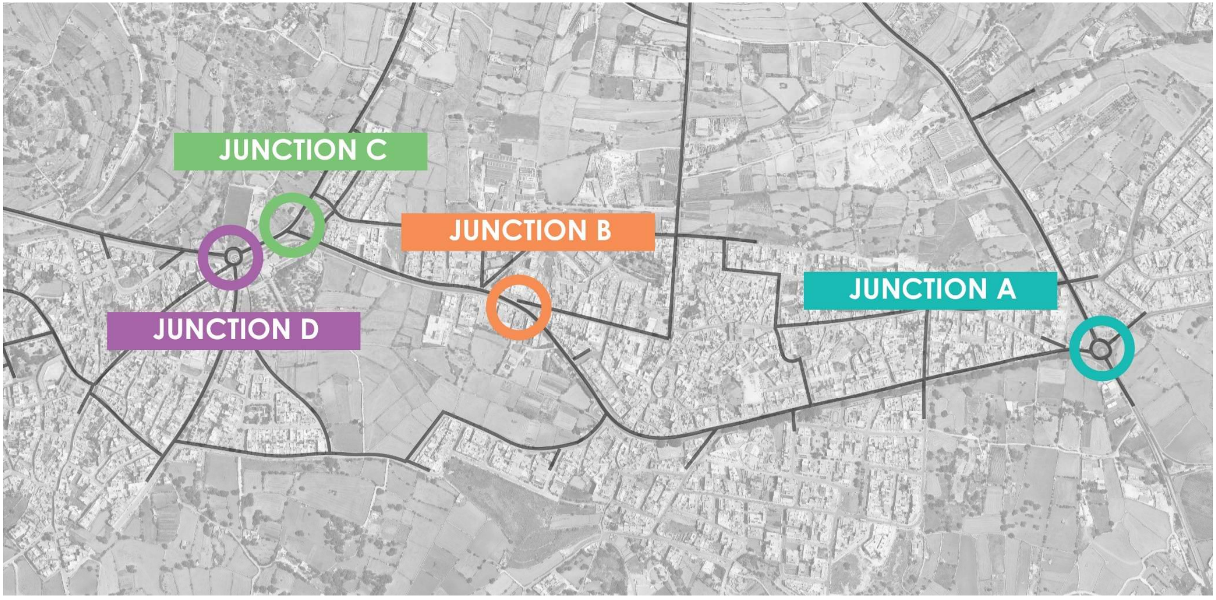


Figure 59. Junction turn movements diagram at Junction B

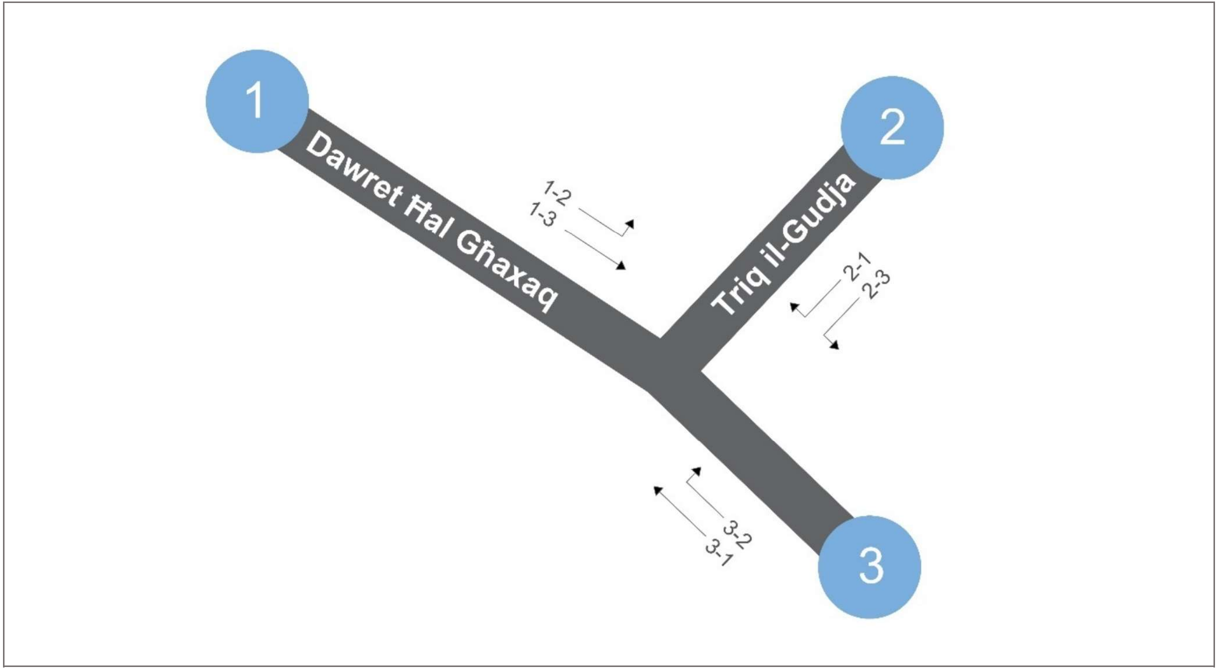


Table 16. Junction turn movements at Junction B compared between scenarios

JUNCTION B			
Turns	**Scenario 1**	**Do-Something 1**	**Do-Something 2**
1-2	2	1	6
1-3	478	209	489
2-1	186	195	175
2-3	6	7	7
3-1	799	220	839
3-2	8	6	8

Figure 60. Junction turn movements diagram at Junction C

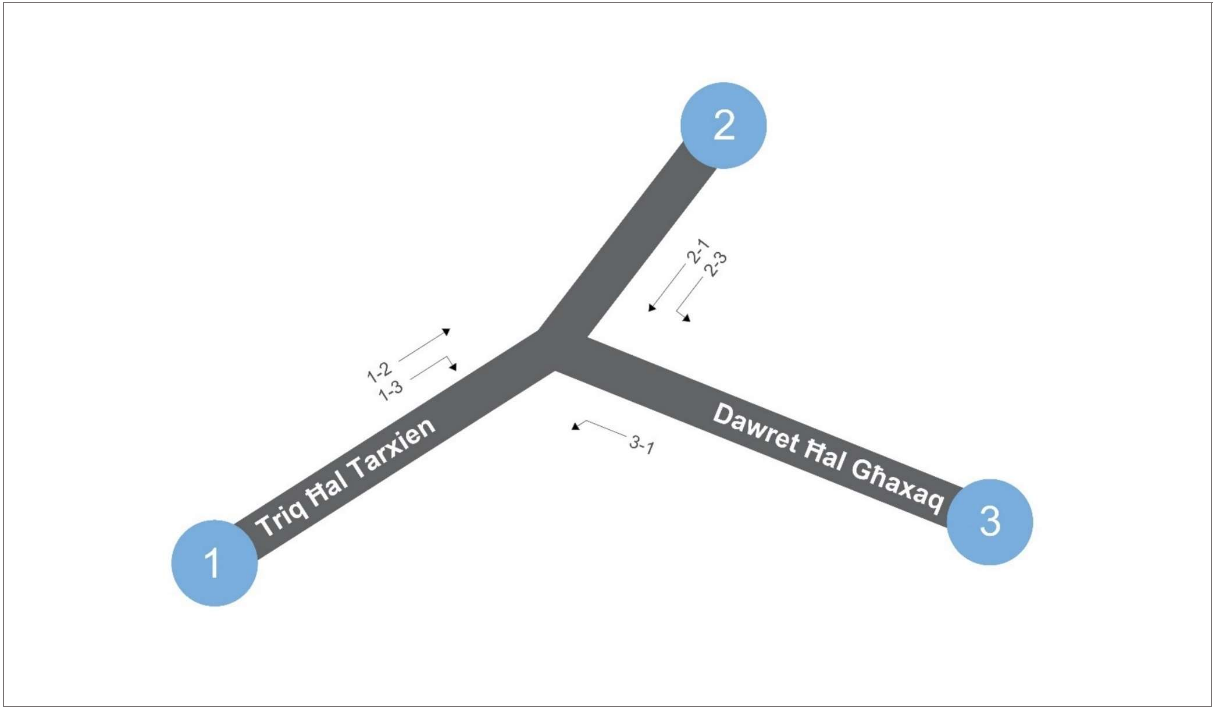


Table 17. Junction turn movements at Junction C compared between scenarios

JUNCTION C			
Turns	**Do-Nothing**	**Do-Something 1**	**Do-Something 2**
1-2	202	227	183
1-3	517	208	544
2-1	192	198	195
2-3	27	23	25
3-1	1090	634	1104

Figure 61. Junction turn movements diagram at Junction D

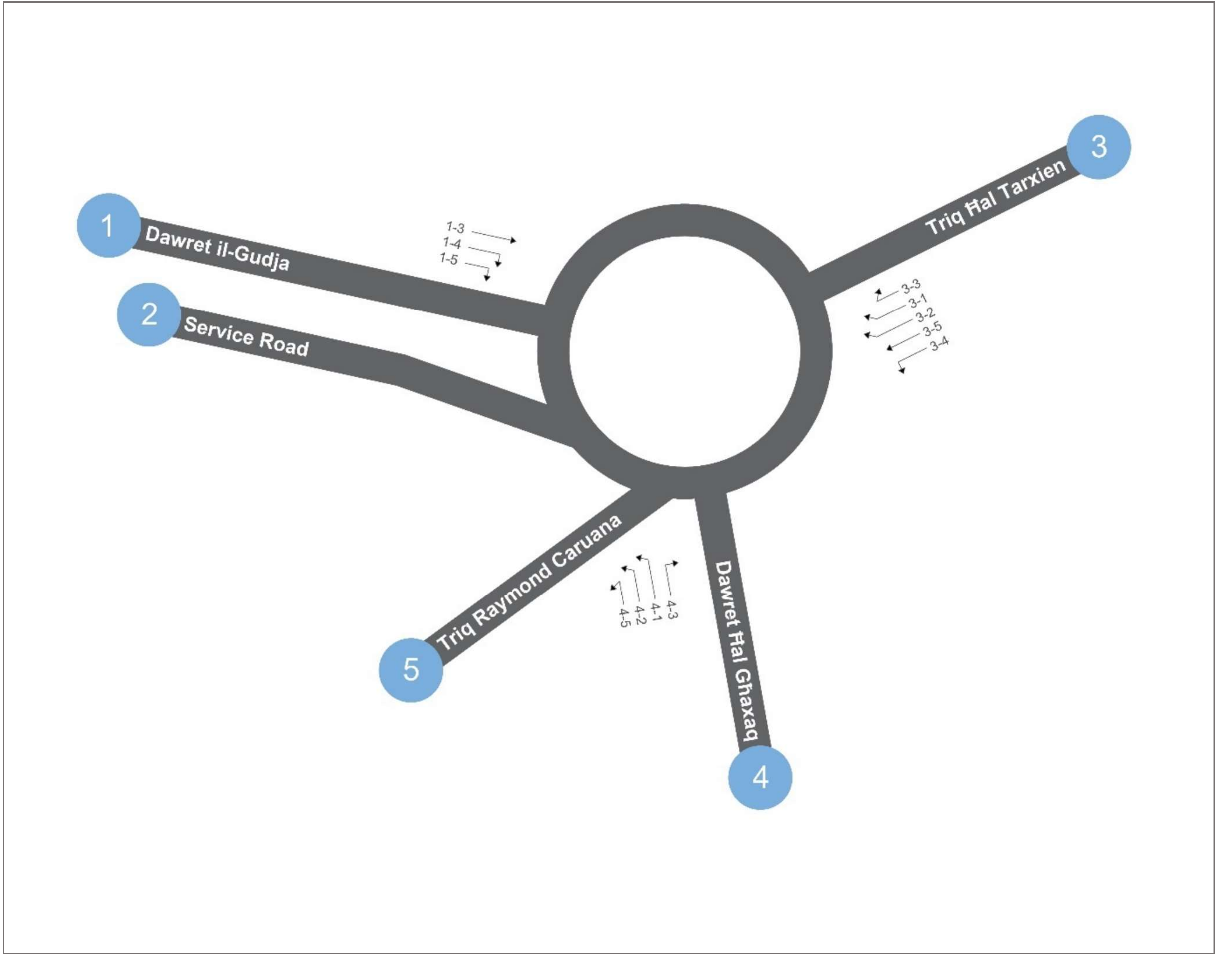


Table 18. Junction Turn Movements at Junction D compared between each scenario

JUNCTION D			
Turns	**Do-Nothing**	**Do-Something 1**	**Do-Something 2**
1-3	567	250	593
1-4	48	47	56
1-5	5	4	5
3-1	1126	678	1116
3-2	27	29	68
3-3	71	64	42
3-4	34	33	30
3-5	27	27	32
4-1	101	140	87
4-2	13	2	15
4-3	124	151	98
4-5	14	17	12

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