Universidade de Aveiro
Departamento de Engenharia Mecânica

Ano 2019

BEHNAM BAHMANKHAH

IMPACTE DA INTERAÇÃO ENTRE VEÍCULOS MOTORIZADOS E BICICLETAS NA ESCOLHA DE ROTA, DESEMPENHO DE TRÁFEGO, EMISSÕES E SEGURANÇA

IMPACT OF MOTOR VEHICLES-BICYCLES INTERACTION ON ROUTE SELECTION, TRAFFIC PERFORMANCE, EMISSIONS AND SAFETY

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Mecânica, realizada sob a orientação científica da Professora Doutora Margarida Coelho, Professora Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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palavras-chave

Modelação em microescala, Análise multiobjetivo, Tráfego, Emissões, Segurança, Volatilidade na condução, Bicicleta.

Resumo

A complexidade inerente à mobilidade em áreas urbanas está associada ao excesso de tráfego e à multiplicidade de origem-destinos, rotas e motivos de viagem. O incremento do uso dos modos suaves, nomeadamente da bicicleta, apresenta benefícios económicos e ambientais, contribuindo para a melhoria da saúde. No entanto, a presença de bicicletas acarreta preocupações ao nível da segurança dos ciclistas. As questões de segurança podem estar relacionadas com movimentos súbitos ou inesperados dos ciclistas, principalmente quando circulam em conjunto com veículos motorizados (VMs), ou quando há uma situação de ultrapassagem entre VMs e bicicletas.

O principal objetivo da Tese de Doutoramento consistiu em quantificar e avaliar o impacto da interação entre veículos motorizados e bicicletas ao nível do desempenho de tráfego, segurança rodoviária e emissões para definir um modelo de análise multiobjetivo. A tese foi focada em três tópicos principais, desenvolvidos com base na avaliação do desempenho do tráfego, segurança e emissões em áreas urbanas: (i) análise multiobjetivo de forma integrada do desempenho do tráfego, emissões poluentes e conflitos rodoviários entre bicicletas e VMs em intersecções sinalizadas; (ii) avaliação da volatilidade de condução em interações VM-bicicleta em rotundas de duas vias e seus impactos na segurança, emissões de poluentes e desempenho de tráfego; e (iii) análise dos impactos ao nível de segurança rodoviária e consumo de energia em vias urbanas, com a avaliaçao da distância lateral de ultrapassagem entre uma bicicleta e um VM. Os dados da dinâmica do velocípede e do VM foram recolhidos e gravados segundo a segundo com um GPS. A metodologia desenvolvida nesta tese foi aplicada tendo por base os estudos de caso associados a diferentes tipos de vias urbanas na cidade de Aveiro, Portugal. O presente trabalho utiliza uma plataforma de simulação microscópica de tráfego (VISSIM), segurança rodoviária (SSAM) e emissões (Potência Específica do Veículo - VSP) para analisar as operações relacionadas com tráfego, questões com segurança rodoviária e estimar o dióxido de carbono (CO_2), emissões de poluentes como o óxido de azoto (NO_X), monóxido de carbono (CO) e hidrocarbonetos (HC). Além disso, para a análise multiobjetivo do desempenho do tráfego, conflitos rodoviários entre VMs e bicicletas, e emissões, o algoritmo genético NSGA-II (Nondominated sorted genetic algorithm II) foi utilizado. As metodologias de Potência Específica de Bicicleta (BSP) e VSP foram usados para analisar os impactos no consumo de energia do ciclista e do veículo, respetivamente.

Os resultados mostraram que, em geral, as rotundas apresentam melhor desempenho de tráfego (número de paragens e tempo de viagem reduzidos em 78% e 14%, respetivamente) e menores emissões (CO_2, NO_X e HC diminuíram 9%, 7% e 12%, respetivamente) quando comparadas a outras interseções, mesmo com elevados níveis de ciclistas (270 bicicletas por hora). Em relação à segurança, o design da rotunda tende a favorecer a ocorrência de conflitos mais graves e potenciais acidentes, apesar do número total de conflitos poder diminuir significativamente (menos 49%). Descobriu-se também que o impacto das velocidades de circulação dos VMs e das bicicletas, bem como o design da rotunda constituem fatores mais importantes do que o volume de ciclistas nas rotundas. Considerando a interação VM-bicicleta numa rotunda de duas vias, os resultados das emissões sugerem boas relações (R^2> 70%) entre as distribuições dos modos de aceleração e VSP. Por fim, os resultados mostraram que em 50% das ultrapassagens a distância lateral entre o velocípede e o VM foi menor que 0,5m, tanto na hora de ponta da manhã como da tarde. Além disso, verificou-se um bom ajuste entre a distância lateral de ultrapassagem e os volumes de tráfego nas horas de ponta da manhã (R^2 = 72%) e da tarde (R^2 = 67%). A metodologia e resultados desta investigação poderão ser utilizados por decisores políticos na área da mobilidade e da segurança rodoviária, câmaras, gestores e engenheiros de tráfego.

Keywords

Microscale modelling, Multi-objective analysis, Traffic, Emissions, Safety, Driving volatility, Bicycle.

Abstract

Mobility in urban areas is highly complex because of the variety of possible facilities and routes, the multitude of origins and destinations, the increase of population and traffic. Increased use of active modes, such as cycling, presents economic and environmental benefits, and contributes to health improvement. However, it can lead to safety concerns such as bicycles sudden or unexpected movements mainly when circulating together with motor vehicles (MVs) or when there is an overtaking situation between MVs and bicycles.

The main goal of this doctoral thesis is to quantify and assess the impact of the interaction motor vehicle-bicycle on traffic performance, road safety and emissions to define a multi-objective analysis model of the impacts regarding the use of motor vehicle and/or bicycle. The thesis was focused on three main topics developed based on the evaluation of traffic performance, safety and emissions at urban areas : (i) to perform a multi-objective analysis in an integrated manner of the traffic performance, pollutant emissions and road conflicts between bicycles and MVs at a signalized intersection; (ii) to assess the driving volatility in MV-bicycle interactions at two-lane roundabouts and its impacts on safety, pollutant emissions and traffic performance; and (iii) to analyze the impacts of the overtaking lateral distance between a bicycle and a MV on road safety and energy consumption at two-lane urban roads.

Second-by-second bicycle and vehicle dynamic data were collected using GPS travel recorders.

The methodology developed in this thesis was applied based on real world case studies at different urban road types in the city of Aveiro, Portugal. The present work uses a microscopic simulation platform of traffic (VISSIM), road safety (Surrogate Safety Assessment Methodology – SSAM) and emissions (Vehicle Specific Power – VSP) to analyze traffic operations, road safety concerns and to estimate carbon dioxide (CO_2), nitrogen oxide (NO_X), carbon monoxide (CO), and hydrocarbons (HC) pollutant emissions. Furthermore, the Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was used in order to address the multi-objective analysis of traffic performance, road conflicts between MVs and bicycles, and emissions. Bicycle Specific Power (BSP) and VSP concepts were used in order to analyze the impacts on cyclist and vehicle energy consumption as well.

The findings showed that roundabouts present, in general, better traffic performance (number of stops and travel time reduced in 78% and 14%, respectively) and less emissions (CO_2, NO_X, and HC decreased 9%, 7%, and 12%, respectively) than other intersections, even with high demand of cyclists (270 bicycles per hour). Regarding safety, roundabout layout lead to more severe conflicts and potential crashes while the number of total conflicts can be reduced significantly (-49%). It was also found that the impact of MVs and bicycles speeds, as well as roundabout design, were more important factors than bicycle volumes at roundabouts. Considering the MV-bicycle interaction at two-lane roundabout, the results of emissions dictated good relationships (R^2 > 70%) between acceleration and VSP modes distributions. Finally, the findings showed 50% of overtaking lateral distance (between bicycle and MV) lower than 0.5m in both morning and afternoon peak hours. Moreover, it was found that there was a good fit between overtaking lateral distance and traffic volumes in morning (R^2 = 72%) and afternoon (R^2 = 67%) peak hours. The findings of this research can be useful for policy makers of the mobility and road safety fields, municipalities, road designers, and traffic engineers.

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NOMENCLATURES

ABW	Alliance for Biking and Walking
Bph	Bicycle per hour
BSP	Bicycle Specific Power
CMEM	Comprehensive Modal Emission Model
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Cph	cyclists per hour
DeltaS	Relative difference between vehicles
DPV	Diesel Passenger Vehicles
DR	Initial deceleration rate
EC	European Commission
EEA	European Environmental Agency
EFC	European Cyclists' Federation
EPA	U.S. Environmental Protection Agency
EU28	European Union 28 Countries
EU14	European Union 14 Countries
EU	European Union
FHWA	Federal Highway Administration
GA	Genetic Algorithm
GEH	Geoffrey E. Havers Statistic
GHG	Greenhouse Gas
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPV	Gasoline Passenger Vehicles
Grade	Terrain Gradient [%]
HC	Hydrocarbons
HCM	Highway Capacity Manual
HDV	Heavy-Duty Vehicles
IMT	Instituto da Mobilidade e dos Transportes
KE	kinetic Energy
LCDV	Light Commercial Diesel Vehicles

LDDT	Light Duty Diesel Trucks
LDV	Light Duty Vehicles
LOS	Level of Service
MAPE	Mean Absolute Percent Error
MCDM	Multi-Criteria Decision Making
MaxD	Maximum deceleration rate
MaxS	Maximum speed between vehicles
MOVS	MOtor Vehicle Emission Simulator
Mph	Miles per hour
MV	Motor Vehicle
NHTSA	National Highway Traffic Safety Administration
NMEA	National Marine Electronics Association
NO_x	Nitrogen Oxides
NSGA-II	Fast Nondominated Sorting Genetic Algorithm
OBD	On-Board Diagnostic System
O-D	Origin-Destination matrices
PBIC	Pedestrian and Bicycling Information Center
PE	Potential Energy
PEMS	Portable Emission Measurement System
PET	Minimum post-encroachment
PM	Particulate Matter
SSAM	Surrogate Safety Assessment Methodology
TTC	Time-to-collision
VISSIM	Verkehr In Städten SIMulationsmodell
Vph	Vehicles Per Hour
VRP	Vehicle Routing Problem
VSP	Vehicle Specific Power

1. INTRODUCTION

1.1. Research motivation

Transportation in urban areas is highly complex because of the variety of transportation modes and routes, the multitude of origins and destinations, increase of population living in cities and traffic.

Rising of demand in urban mobility for people and goods is a significant challenge. The strong externalities such as air pollution and climate change are going to be ever more important, besides the other criteria such as time, distance, congestion and price (McNicol et al., 2001; Tzeng et al., 2005; Pucher et al., 2011a; 2011b). Furthermore, passengers are more interested about environmentally friendly routes and to use active modes (such as cycling) to do short-distance trips in urban areas. Moreover, safety is one of the main concerns for road users especially for cyclists as vulnerable users in urban areas.

Cycling demand is increasing every day in high-density areas. Individual health benefits of cycling along with positive effects on air pollution and environmental issues have led to the increase of cycling rate worldwide (Van Hout 2008; Winters et al., 2013). In some countries, the agencies and government ministries give attention to cycling as the main transportation mode by providing appropriate structures and facilities for cycling in the regional transportation system (Pucher and Buehler, 2008; ABW 2010; PBIC and FHWA, 2010). Cycling offers some important financial, health and social benefits to the users and the environment. Besides these important advantages, bicycle offers sometimes the fast transportation option for short-distance trips. It seems that because of this reason the rate of cycling in European small cities is higher than big cities (Pucher et al., 2011c) and they can offer better traffic performance compared to motor vehicles. Increasing the awareness of people about the details and results of their decision about using the motor vehicle or bicycle for their trips can help them to plan their travel in urban areas by choosing the best vehicle. In fact, drivers have not always enough information to identify, among numerous routes, what is best for the economy and the environment (Bandeira 2013).

1.1.1. The importance of cycling in urban transportation

The risk and cost of using a motor vehicle in urban areas, air pollution and noise, millions of hours spent on traffic and the positive impact of cycling on health and quality of life are some of the key factors that encourage people to cycle more (Buis and Wittink, 2000; PBIC and FHWA, 2010).

Public transportation is one of the most important alternatives to the motor vehicle but sometimes for short distances (5 km and even more for in the case of traffic congestion), cycling can be the best alternative to go easy and fast. Furthermore, based on data released by the European Commission, about urban transportation, almost half of all the motor vehicle trips are over distances of shorter than 5 kilometers (EC 2016). It means that cycling can replace the motor vehicle use for 50% of the urban transportation network (EC 2007).

In 1990, cycling and walking were described as “the forgotten modes” of transportation by the Federal Highway Administration (FHWA). Then in 1994 the new transportation policy reported in United States (PBIC and FHWA, 2010): “increase use of bicycling, and encourage planners and engineers to accommodate bicycle and pedestrian needs in designing transportation facilities for urban and suburban areas, and increase pedestrian safety through public information and improved crosswalk design, signal controls, school crossings, and sidewalks.”

As same as US (Pucher et al., 2011c), also in Europe the demand for cycling is increased throughout the time. In some of the European countries such as Denmark, Germany and Nederland cycling is defined as the main transportation mode for urban transportation network at a high level (Pucher and Buehler, 2008).

Pucher et al. have developed comprehensive research about cycling in urban transportation since 1999. The first published paper was about cycling renaissance in America (Pucher et al., 1999) and since then they have done several useful surveys in different countries such as Europe (Pucher and Buehler, 2007; 2008; Buehler et al., 2012; Buehler et al., 2016), United States (Pucher and Buehler, 2006; 2009; Pucher et al., 1999; 2010b; 2011a; 2011c; Buehler et al., 2012), Canada (Pucher 2005; Pucher and Buehler, 2006) and Australia (Pucher et al., 2011b; Buehler et al., 2012; Buehler et al., 2016) among others.

Regards to the potential demand for cycling around the world the number of bicycle stations and bicycle-sharing systems is increased more than past. There are some other important reasons that influence bicycle users to put this vehicle as the main facility for short distance trips in urban areas. Besides the economic issues, there is big a challenge to reduce emissions. The positive impact of replacing motor vehicles by bicycles in urban areas is the improvement of traffic performance and emissions (Rojas-Rueda et al., 2012).

The important role of cycling for countries is going beyond the social, economic, environmental and individual benefits. Even political advantages can be gained for countries by cycling, such as a reduction in dependence on energy and saving non-renewable sources. Furthermore, it can bring other advantages for local governments and municipals, such as space saving for a city, helping to solve the motor vehicle parking space problems, increasing the welfare of citizens and especially the people who are living in the city center.

Many cities in the world seek to change their transport systems in favor of buses, trams, trains, cycling and walking, as a result of increasing levels of local air pollution, emissions of greenhouse gases, accidents, and traffic congestion. Reduction in travel by motor vehicles, especially by private motor vehicles in urban network, is needed to meet targets for the reduction of greenhouse gas (GHG) emissions in the transport sector besides the important health benefits. Furthermore, in addition to GHG, other transportation-related air pollutants such as nitrogen oxide (NOx), particulate matter (PM), hydrocarbons (HC) and carbon monoxide (CO) have significant negative effects on human health such as problems on the cardiovascular system, lungs, liver, spleen, and blood.

1.1.2. Why multi-objective analysis for urban transportation?

Since 1959, Vehicle Routing Problem (VRP) was considered as a mathematical and algorithmic approach in transportation studies so far (Golden et al., 2008). During the time thousands of models have been developed for several vehicle routing and optimization problems. These models have been created based on the nature of identified problems, the structure, the attitudes and the complexity of the case study (Eksioglu et al., 2009).

Several studies have been conducted bicycle routing and sharing/distribution optimizations problems as a part of the VRP using different models and algorithms (Lin and Chou, 2012; Raidl et al., 2013; Di Gaspero et al., 2016). Bicycle routing and sharing investigations were helpful for VRP in different concepts as well. Some researches inspired their theories and ideas of bicycles redistribution concept in vehicles rebalancing optimization problems (Di Gaspero et al., 2016).

Regards to the complexity system of transportation network in urban areas, the variety of possible facilities to move from one point to another (i.e. motor vehicle, bicycle, bus, motorcycle and etc.) and the variety of objectives (i.e. minimizing the time, cost, energy, environmental concerns and increasing safety) seems that multi-objective optimization can be the best option to evaluate the vehicle's routing network in urban areas in order to find the best path to use. Moreover, the main aim is to optimize the identified objectives simultaneously.

Multi-objective analysis is an area of multi-criteria decision making which accept several numbers of criteria and alternatives to evaluate them in a specific framework. Furthermore, multi-criteria decision-making area is one of the main and popular resources for researchers for solving transportation problems (Mardani et al., 2015).

It seems that in the field of transportation the number of multi-objective studies increased significantly. Although most of the multi-objective studies in traffic engineering have been used two-dimensional optimization methods only a few studies have focused on three-dimensional solutions (Stevanovic et al., 2015; Fernandes et al., 2015). Furthermore, sometimes improving one of the traffic parameters can make the worst situation for other safety and environmental concerns simultaneously. In this way, multi-objective analysis can be a good tool to find a balanced solution for all traffic, emissions and safety concerns.

Researchers use various methods and techniques in solving complex problems in transportation network systems. These methods can be applied based on the problem's structure and relevant alternatives. The attributes and type of vehicles (Gursoy 2010), characteristics and constraints of routing problems, the complexity of designed routes in urban network transportation systems, traffic and pollution leads to increase the interest of researchers to develop the real world applications in transportation and logistics areas (Kazan and Çiftci, 2013).

The routing optimization problem belongs to the model known as the Vehicle Routing Problem (VRP). Vehicle routing problems have been received a great deal of attention since as early as the 1960s. The vehicle routing problem is first introduced in 1959 by Dantzig and Ramser. They assigned a real application of fuel delivery to fuel pump stations by proposing the first mathematical formulation and algorithmic approach (Golden et al., 2008). Then in 1964, Clarke and Wright published an algorithm for vehicle routing problems which was as an improved method about Dantzig and Ramser's algorithmic approach. These two papers provided good opportunities for other researchers about thousands of VRP models and algorithms so far (Eksioglu et al., 2009).

Multi-objective optimization is an area of multi-criteria decision making (MCDM). Based on the number of the criteria and alternatives the function can be defined to optimize the involved objectives simultaneously. If the identified criteria are multiple conflicting criteria in this condition they need to be evaluated by MCDM models (Singh and Malik, 2014).

There are a lot of criteria in transportation area that can influence the impacts of transportation on the environment, economy and social life of people. The type of fuel, speed, applied technology by vehicles producers, driver's behavior, transportation infrastructures, travel distance are just some of the important factors that can effect on air quality, climate change, energy consumption, safety and health, and cost of travel, among others (Mahmoodzadeh et al., 2007; Kazan and Çiftci, 2013).

1.2. Impacts of interaction motor vehicle-bicycle – a literature review

1.2.1. Perceptions regarding the case of motor vehicles and bicycles

Much of the research has been focused on vehicle performance and the interaction between them at traffic networks in urban and suburban networks. One area of research that has not received as much attention in the past is the vehicle performance regarding the interaction motor vehicle-bicycle through traffic networks in urban areas. Currently, the daily average trip by motor vehicle for Portuguese and European (EU-28) is between 10-15 km and 22-26 km, respectively (EEA 2014; IMTT 2015). The average distance trip by bicycle is 10 km per person per year while the average distance for EU-14 is 186 km per person per year. Among the EU-14 countries, Denmark with 893 km is in the top and Spain with 20 km is the worst (Van Hout 2008).

Urban trips from an origin point to a destination may include a private motor vehicle, public transport, walking, bicycle or other active modes. Using a bicycle for urban trips can bring significant positive results for users and environmental (Twaddle et al., 2014; Silvano et al., 2015). Reduction in the use of motor vehicles could reduce urban air pollution and lead to large health benefits. Health, safety, and social equity will all benefit from more cycling and less motor vehicle driving (Van Hout 2008). Passengers can set their urban trip plan including multimodal combinations such as motor vehicle-train-bicycle or train-bicycle and other combinations. Nonetheless, in this thesis, the research is focused on the traffic performance, emissions and safety concerns using motor vehicle-bicycle for urban trips. In this way, analyzing the impacts of motor vehicle-bicycle interactions in the urban network is the main subject of the work.

In general, travelers prefer to use some form of minimum-cost or minimum-distance route from their origin point to their destination. In this case, a bicycle can be introduced as the best option. For some trips passengers do not prefer to use bicycle regarding the dangerous traffic conditions, lack of bicycle infrastructure facilities, physical exertion (especially in hilly terrains) and adverse weather conditions (Stinson and Bhat, 2004). However, beyond these important factors, some others such as road grade, road type, and vehicles volumes can affect passengers´ decision to not use a bicycle for short distance trips.

Sometimes cyclists are traveling in the lane and in the same direction as adjacent motor vehicles. In this condition, it is needed to focus on cyclists and drivers behaviors to evaluate urban traffic performance. Cyclists and drivers behavior can play an important role regarding the safety concerns and energy consumption. The experience of bicycle users and drivers can affect the interaction between them. Different interaction performance between motor vehicles and bicycles and different impacts of this interaction were analyzed in previous research (Lenden et al., 2000; Buis et al., 2000; Ker et al., 2005; Van Hout, 20008; Ryus et al., 2011; EPA 2012; Rojas-Rueda et al., 2012; Winters et al., 2013). Delay, speed, queue, flow rate and Level-Of-Service (LOS) are some of the important traffic factors which can be analyzed regarding the motor vehicle-bicycle interaction. Furthermore, the impact of this interaction on safety and emissions is one of the other important aspects of the work.

Transportation‘s National Highway Traffic Safety Administration and Transportation Research Board have analyzed the perceptions and travel behavior of cyclists in the US (Ryus et al., 2011). It would have been important, in this research, to have the parameters describing the interaction between cyclists and motor vehicle drivers. Speed, delay and the conflicts can be proposed as the main factors which can be analyzed theoretically and practically in a case study.

If the bicycles number is not compatible with the capacity of a lane and if the cyclists are using the same lane of motor vehicles the delay time and even number of conflicts will be increased for both drivers and cyclists (demand variation). HCM 2010 reports that in two conditions the delay for cyclists will be more than the obtained value based on the existing formulas; when (i) cyclist are forced to weave with right-turning traffic duration the green indication, or (ii) drivers do not acknowledge the bicycle right-of-way because of high flows of right-turning vehicles. The delay time for cyclists is important as same as drivers and it could affect the traffic performance when they are using the same lane with motor vehicle drivers. The results show that in general cyclists tend to become impatient when they experience a delay in excess of the 30s/bicycle (Ryus et al., 2011). In this case, they may decide to change the lane or try to overtake the front vehicle and it can lead to accident risk or increasing the delay for other vehicles.

The geometric specification of cyclist lane, the infrastructure capacity (Ker et al., 2005) and the level of service are some of the major concerns that can increase or decrease the impact of traffic performance regarding the motor vehicle-bicycle interaction. These important factors can change passengers' travel behavior by using alternative travel facilities instead of a bicycle. Regarding the size of bicycle, using more bicycle instead of motor vehicle can improve the lane utilization in urban areas. According the official guidelines from Danish Road Directorate (Van Hout 2008) a 2 m wide one-way cycle way has a capacity of 2000 cyclists while is actually able to unroll 5200 cyclists per hour.

1.2.2. Emissions impacts of interaction motor vehicle-bicycle

Almost a quarter of all greenhouse gases originate from motor vehicle tailpipe emissions (Kahn 2007). Drivers' behavior and traffic performance have the most direct impact on emissions.

Regarding the low speed of cyclist among other motor vehicles by increasing the delay time due to number of stop-and-go for the vehicles, it can cause to more energy consumption and emissions. The interaction between a bicycle and motor vehicle can lead to more emissions because of delay, speed, and drivers' behavior (cyclists and motor vehicle drivers). Furthermore, depending on the physical characteristics of each road the motor vehicle-bicycle interaction can lead different amount of emissions as well (such as uphill). It is clear that the narrow and not physically separated lane for a cyclist can increase the traffic density and due to more emissions.

The number of bicycles and cyclist travel behavior can reduce the maneuverability of motor vehicles and force them to have more acceleration and deceleration behavior (Wang et al., 2015; Liu et al., 2017). Acceleration and deceleration of a vehicle is one of the important behavioral factors that increase the amount of produced emissions. This traffic condition can lead to multiple stops, queue formation. Vehicle emissions will increase with the occurrence of more delays, queue and multiple stops (Coelho et al., 2006). In this way, the role of a cyclist is more important than other motor vehicle drivers because they travel at low speed. Moreover, because of safety concerns, drivers' behavior can change by giving more time to the cyclist because of collision risk.

Intersections and roundabouts are the critical traffic points of urban networks (Götschi et al., 2016). The produced emissions of vehicles in these areas is higher than other urban areas (Salamati et al., 2015). Moreover, according to the signals and traffic interactions between vehicles, these urban areas are complex but the presence of bicycles can increase the complexity of these areas.

For better analyzing the emission impacts of motor vehicle-bicycle interaction, it would be better to identify the factors that could affect this interaction and lead to increase or decrease the amount of emissions. Moreover, it seems that all the interaction factors between motor vehicles such as speed, delay, conflicts, number of vehicles, drivers' behavior, the geometric specification of place and etc. can be defined for motor vehicle-bicycle interaction. Furthermore, a bicycle has some specific characteristics that can lead to different results. For example, the delay between motor vehicle-bicycle interactions is different than two motor vehicles. Regarding the low speed of bicycle and safety risk, the delay travel time between one motor vehicle and bicycle is more than the delay that occurs between two motor vehicles. Regarding the existing relationship between delay and emissions, it would be concluded that the produced emissions of motor vehicle-bicycle interaction are more dependent on the delay that causes by a cyclist to motor vehicles.

It is to be noted that beyond these details the role of traffic density, type of traffic intersections and traffic capacity are some of the other important factors that can highly affect the produced emissions regarding the motor vehicle-bicycle interaction.

1.2.3. Safety impacts of interaction motor vehicle-bicycle

It would be important to identify and describe the factors that could influence the safety risk of interaction between a cyclist and motor vehicles in order to improve the cyclists' safety.

The physically separated lane for bicycle at mixed traffic situation has a significant positive effect on safety (Winters et al., 2013).

Although regarding the maneuverability of cyclists they can manage to swerve around the motor vehicles (Leden et al., 2000) but sometimes they cannot stop or runaway from danger when motor vehicles brake suddenly. In this situation of interaction between a motor vehicle and bicycle, the risk of collision increase to cyclist but the experience of cyclist can be helpful to avoid accident occurrence.

Conflicts between motor vehicles and bicycles may result in crashes in the urban network. However, it is one of the main safety concerns of a cyclist for not regularly use of a bicycle in roads (lack of road safety). Policies that encourage people to cycle would be expected to increase the safety of travel. Subsequently, increasing the number of cyclists in urban transportation scenarios could increase the risk of collision as a result of motor vehicle-bicycle interaction. In other words, reducing motor vehicle use in the urban transportation system would decrease the injury risk for existing cyclists when cyclist volume increase.

Regarding the size of the bicycle when a cyclist is riding behind a large vehicle, like a bus or especially heavy vehicle, the visibility of cyclist and another driver will be poor. This scenario can increase the risk of collision and injury for the cyclist. For a cyclist, it would be difficult to make a decision how to overtake the vehicle that is located in front of the bicycle but for motor vehicle driver may be difficult to see the bicycle that is located behind the vehicle. In this scenario, the risk of collision will be increased when the driver decides to move turn right or left.

Other important factors regarding the safety impacts of a motor vehicle-bicycle interaction could be human factors such as driver expectations and driver behavior. In fact, the increase of cyclists and motor vehicles' speed is a sign of risk that can occur when there is an overtaking situation between a bicycle and a motor vehicle (Leden et al., 2000).

Further details about important safety factors regarding motor vehicle-bicycle interaction can be found elsewhere (Laden et al., 2000; Buis et al., 2000; Ryus et al., 2011; EPA 2012; Silvano et al., 2015; EC 2017).

1.3. Research gaps

Table 1.1 represents the summary of literature review based on the applied methodology and the area of its application.

Table 1.1. Techniques and applied model from literature review.

Refrences	Subjects	Limitations
Ahn et al., 2009	Energy and environmental impact of an isolated roundabout on a high speed road.	The INTEGRATION and VISSIM software were employed to simulate driving patterns and on-road emission measurement equipment (OEM) was used to estimate energy consumption.
Bandeira, 2013	Road traffic information platform for energy and emissions savings.	Route choice based on environmental concerns (The integration of empirical and analytical methods to assess the impact of different traffic optimization strategies on CO_2 emissions and local pollutants).
Buis & Wittink, 2000	The Economic Significance of Cycling.	Cost-benefit analyses of bicycle policies.
Dantzig & Ramser, 1959	The truck dispatching problem (The paper is concerned with the optimum routing of a fleet of gasoline delivery trucks between a bulk terminal and a large number of service stations supplied by the terminal).	Vehicle Routing Problems (VRP was focused more on truck vehicles - No flexible to different models - lack of support and complementary optimization tools).
Di Gaspro et al., 2016	Application of Constraint Programming to solve the problem of balancing bicycle sharing systems based on VRP concept.	Including the role of both bicycle (*i.e.* number of bicycles at each station) and vehicles (*i.e.* truck capacities) in optimization method.
Fernandes et al. 2015	Multi-criteria Assessment of Crosswalk Location in Urban Roundabout Corridors.	Simulation platform of traffic (Vissim), emissions (VSP) and Safety (SSAM). The Fast Non- Do inated Sorting Genetic Algorithm (NSGA-II) was applied on this study.
Golden et al. 2008	Vehicle Routing Problems; Latest, advanced and new challenges (Book).	SAS - genetic algorithms - linear optimization - metaheuristics - modeling – multi-period routing vehicle routing.
Gursoy, 2010	deals with the problem of choosing the best possible shipping alternative among a set of transportation modes considering four decision criteria.	AHP- identified criteria are: Safety, price, time and accessibility- transportation mode selection (road-sea-rail)

Kazan & Çiftci, 2013	The aim of the study is to research which factors are important among speed, reliability, capacity, suitability, cost, and safety, and accessing the criteria that which one(s) must be selected	AHP& PROMETHEE - The number of evaluated criteria can be developed more. Ex) environmental concerns - transportation mode and most important criteria selection
Li et al., 2015	Simulation-based Traffic Signal Optimization to Minimize Fuel Consumption and Emission: A Lagrangian Relaxation Approach.	Application of VISSIM and MovesLite - Signal optimization.
Lin & Chou, 2012	Bicycle redistribution balancing between public bicycle stations using VRP optimization method.	Minimizing travel distance and time of bicycles considering real-world road conditions provided by Google Directions – Application of heuristics method for actual path distance optimization.
Mardani et al., 2016	Multiple criteria decision-making techniques in transportation systems.	MCDM – Literature review in transportation
Mohmoodzadeh et al., 2007	Project (logistic) Selection by Using Fuzzy AHP and TOPSIS Technique.	AHP and TOPSIS application for logistic project selection. Some identified criteria cannot develop to others in ranking projects of differing sizes or levels of investments.
Raidl et al., 2013	Balancing bicycle sharing system improvement based on VRP concept.	Development of a method for calculating proven optimal loading operations of bicycles at stations.
Rojas-Rueda et al., 2012	Impacts of replacing cars with bicycles and public transport on individual health.	The paper is focused on health benefits but not traffic safety concerns
Silvano et al., 2015	Bicycle- Motor vehicle interaction analysis at roundabout	This research provides insights into factors (only speed and position of bicycle and vehicle) influencing car drivers' yielding decisions when they interact with cyclists – only one roundabout.
Stevanovic et al., 2015	3-dimensional multi-objective optimization of traffic signals considering mobility, safety, and emissions.	VISSIM, CMEM, and VISGAOST models integration without considering the bicycles.
Twaddle et al., 2014	VISSIM is quite capable of realistically depicting bicycle traffic in most situations considering its limitation	Bicyclists in VISSIM do not interact realistically with the edges of the infrastructure – Bicycles cannot do maneuverability in queue.
Tzeng et al., 2005	Multi-criteria analysis of alternative-fuel buses for public transportation.	(AHP, TOPSIS and VIKOR) Using MCDM approach to find the best fuel alternative - The developed model cannot use for route or type of vehicle selection.
Winters et al., 2013	Safety analysis of cyclists based on infrastructure.	There is no evaluation regarding emissions and traffic performance

1.4. Research objectives

This thesis aims to raise the passenger’s awareness about how to use different scenarios to move from an origin to a destination in urban areas using a bicycle or a motor vehicle. Thus, the main goal of this research is to quantify and assess the impact of the motor vehicle-bicycle interaction on traffic performance, road safety and emissions to define a multi-objective analysis model of the impacts regarding the use of motor vehicle and/or bicycle.

The specific objectives of this research are:

First objective – To evaluate the traffic performance, pollutant emissions and road conflicts between bicycles and motor vehicles in an integrated manner at a signalized intersections considering a multi-objective analysis.

Second objective – To improve the urban network mobility in order to decrease traffic congestion, road conflicts between road users and pollution by developing a multi-objective model for passengers in urban transportation network for short trips using bicycle or motor vehicle.

Third objective – To assess the role of driving volatility in motor vehicle-bicycle interactions at two-lane roundabouts and its impacts on safety, pollutant emissions and traffic performance

Fourth objective – To analyze the impacts of the overtaking lateral distance between a bicycle and a motor vehicle on road safety and energy consumption at two-lane urban roads

Promoting the use of the bicycle for short-distance trips and paying more attention to traffic congestion, environmental concerns and safety are defined as one of the important aspects of this work as well.

Findings from this thesis can be helpful for passengers to provide a systematically regular evaluation of routes in urban areas. Furthermore, may help the policy makers and traffic managers who are working on urban transportation network system design to make a better strategic decision for the future.

1.5. Research contributions

This thesis is focused on the development of a multi-objective approach for passengers in urban transportation network for short trips, where travel distance is less than 5 km. Passenger cars and bicycles are the alternatives which are defined for passengers to use them to move from departure point to a destination.

The present work combines two main sections: theoretically and practically sections. In the first section, the thesis focuses on research problems and objectives definition. Furthermore, this section presents a comprehensive literature review to understand the research gaps and to select the compatible methods for this research and represents the methodology frame structure with the applied methods for quantify and assess the traffic performance, emissions and safety. The outputs of the theoretical part of the thesis will be integrated on a practical platform that is defined as a case studies for the practical section of the thesis (chapters 3, 4, 5 and 6). The case study of this thesis is designated in an urban transportation network in Aveiro city and the achieved results can be applied for the cities with a similar scale and shape. It is has to be emphasized that the findings cannot be generalized for all the urban transportation networks (for example for long distance trips where travel distance is more than 10 km). The study evaluates the main alternatives and criteria about urban transportation areas by creating a multi-objective model to analyze the vehicle and bicycle routing in an identified network of urban area.

In this thesis, the transportation impacts selected with route choices modeled using an integrated three-dimensional multi-objective model to achieve all identified goals simultaneously. Improvement of traffic performance, emissions and safety but simultaneously could be defined as the main novelty of this thesis considering the role of motor vehicle-bicycle interactions at urban areas.

Two-dimensional multi-objective optimization has been used a lot for solving transportation problems. While about 3-dimensional multi-objective optimization application in this area there are no many studies yet (Stevanovic et al., 2015; Rahimi et al., 2017). Several studies have been transformed a multi-objective optimization model to different single objective models in order to simplify their models (Jiao and Sun, 2014). Also among the studies that have mentioned in this methodology, we have not seen the role of cycling mode and most of them have focused only on motor vehicles. To bridge the gap in the existing knowledge this thesis presents a methodology where three-dimensional Pareto Fronts, which are expressed through traffic performance, safety and emissions, are optimized by use of a mathematical function.

Rather than finding the “correct” decision, the identified multi-objective model and the applied techniques help us to find the one that is more suitable for each case and user´s preferences.

Finally, the results could be used in the cities which are in the same scope and characteristics of the thesis case studies. It can be useful for transportation policy makers in order to include traffic, emissions and safety impacts of urban areas in their decisions. Furthermore, the findings could help transportation engineers to better design the urban network for cyclists considering their safety concerns.

Regarding the traffic performance the thesis focuses on delay, travel time and traffic flow, about the emissions the evaluation is based on $CO_{2,}$ CO, HC and NO_X pollutants and finally regarding the safety, number of conflicts, relative speed between vehicles and time to collision (TTC) are the main factors that are analyzed in baseline and alternative scenarios of this research.

1.6. Outline of the document

The thesis will be divided into seven chapters. In chapter one an introduction is done to the outline of the study background, objectives, research questions and scope of the study. This chapter explains the background of cycling in urban transportation and reports the novelty of the work. The structure of the thesis is included in this chapter that represents the relationship between the main context and the published papers (**Table 1.2**).

Chapter two explains an overview and the methodology used in carrying out the study with emphasizing to the methods used to analyze the collected data and information. Also includes a discussion about the impacts on traffic performance, safety and emissions. This chapter also details the procedures, the baseline scenario, alternative scenarios, impact and data analysis conducted in the research.

Chapter three is focused on cycling at intersections. In this chapter, the impact of cycling on traffic performance, emissions and cyclists' safety were analyzed based on a multi-objective view.

Chapter four reports a multi-objective analysis apply for short distance trips in urban areas. This chapter explains how to select an optimum route for a bicycle or motor vehicle based on the three main criteria simultaneously: traffic performance, emissions and safety.

Chapter five explains the impact of motor vehicle- bicycle interactions at roundabouts in a multi-objective view. This chapter analyzes the role of driving volatility on traffic performance, emissions and safety.

Chapter six looks at motor vehicle overtaking maneuvers of bicyclists in an urban traffic corridor at a two-lane road with traffic signals. This chapter analysis driving volatility and traffic volume impact on overtaking distances variation.

Finally, chapter seven focused on the main conclusions of the thesis and recommendations for future work.

Table 1.2. Relationship between the structure of chapters and published articles.

Chapter	Reference paper
3	Bahmankhah, B., Fernandes, P., & Coelho, M. C. (2019). Cycling at intersections: a multi objective assessment for traffic, emissions and safety. *Transport*, *34*(2), 225-236.
4	Bahmankhah, B., & Coelho, M. C. (2017). Multi-objective optimization for short distance trips in an urban area: choosing between motor vehicle or cycling mobility for a safe, smooth and less polluted route. *Transportation Research Procedia*, *27*, 428-435. Bahmankhah, B. and Coelho, M.C., 2018. Impacte da presença de ciclovias no desempenho do tráfego rodoviário, segurança rodoviária e emissões de poluentes em áreas urbanas, 1a Conferência internacional de ambiente em língua Portuguesa, Aveiro, Portugal, 8-10 May.
5	Bahmankhah, B.; Fernandes, P.; Teixeira, J. & Coelho, M.C. (2019). Interaction between motor vehicles and bicycles at two-lane roundabouts: a driving volatility based analysis. *International journal of injury control and safety promotion*, 26:3, 205-215.
6	Behmankhah, B.; Fernandes, P., Ferreira, J., Bandeira, J., Santos, J., Coelho, M. C., (2020). Assessing the Overtaking Lateral Distance Between Motor Vehicles and Bicycles - Influence on Energy Consumption and Road Safety. In: *Macioszek E., Sierpiński G. (eds) Modern Traffic Engineering in the System Approach to the Development of Traffic Networks*. TSTP 2019. Advances in Intelligent Systems and Computing, 1083. Springer, Cham.

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2. METHODOLOGY AND METHODS

2.1. Methodological framework

Structure of this thesis that is used for the selected part of the transportation network in Aveiro city is based on the real world extracted data from case studied plus the literature included in the previous section.

Figure 2.1. Presents a framework of methodology that was applied for this research.

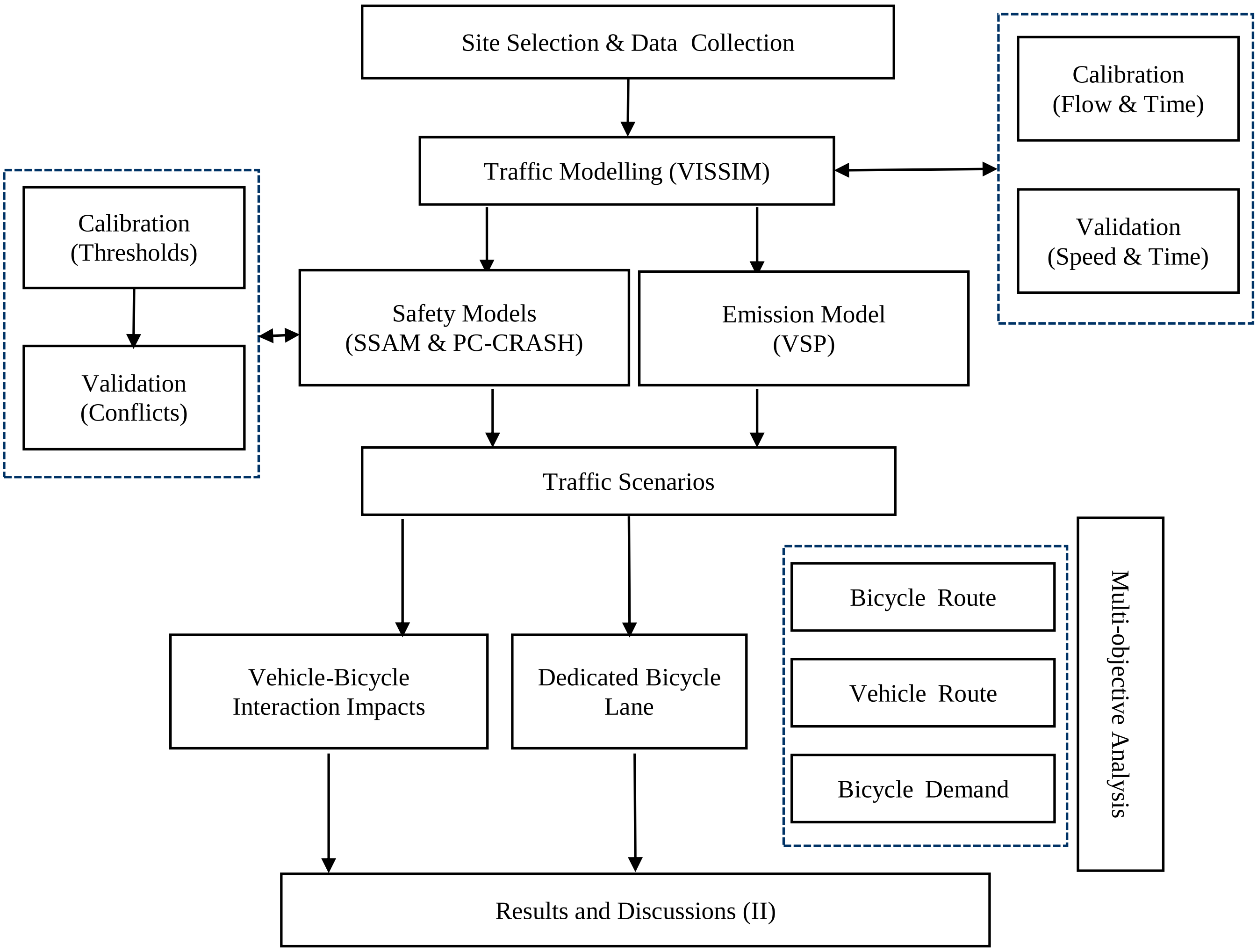

Figure 2.1. Methodology framework.

The traffic operation was videotaped in the selected routes of case studies and the necessary data were extracted from these video tapes and analyzed using VISSIM software. Depends to the case study, VISSIM traffic model was initially calibrated to

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reproduce based on motor vehicle/bicycle traffic flows or travel time. Then, driver behavior parameters of VISSIM traffic model (car following – average standstill distance, additive and multiple part safety distance; gap acceptance – visibility, front and rear gaps and safety distance; and lane change – waiting time before diffusion, min-headway, safety distance reduction factor and maximum distance for cooperative breaking) were adjusted with the main purpose of assessing their impact on traffic volumes or average travel (Fernandes et al., 2016).

Some statistical tools, such as modified chi- squared statistics Geoffrey E. Havers (GEH) which and Mean Absolute Percent Error (MAPE) were used to compare the observed and estimated data and also to measure the size of the error (deviation) between them, respectively (Dowling et al., 2004; Buisson et al., 2014).

Regarding model validation, a comparison of observed and simulated data such as motor vehicle/bicycle speed and travel time were conducted at least in the main codded links using the optimal VISSIM calibrated parameters.

Data were collected in two phases. In the first phase, data were transferred from the videotapes and entered into VISSIM and the outputs were entered to VSP and SSAM model.

After analyzing a 3-leg intersection as a critical point in the entrance of the network (chapter 3), all the possible routes were assessed between origin and destination of the case study (chapter 4). Based on the number of the criteria and alternatives the function can be defined to optimize the involved objectives simultaneously (Singh and Malik, 2014). Due to the variety of the objectives a multi-objective model is defined to deal with the complexity of the urban mobility system. In this model, two alternatives are predetermined for short-distance trips: (*i*) using only motor vehicle to access from one place to another, (*ii*) using only bicycle. The methodology continued using different tools to assess the motor vehicle- bicycle interactions at different parts of the urban area.

This work has compared traffic performance based on delay and queue, examines the carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NOx) and hydrocarbons (HC) emissions and furthermore, the safety factors being produced before and after the application of the alternatives scenarios.

The present work contains a microscopic simulation platform of traffic (VISSIM) for traffic model (PTV AG 2016) and Vehicle Specific Power (VSP) emission estimation methodology was used to quantify the emissions produced by vehicles at the intersection (Frey et al., 2002). These two models were applied to a fleet mostly composed of light-duty vehicles. Overall pollution estimation was provided by integrating traffic and emission models and linking them with various driving patterns at different roads type of the case studies (intersections, roundabouts and traffic lanes). Furthermore, regarding the importance of safety concerns for bicycle users, SSAM model was applied to assess the safety factors for both identified scenarios. The alternative scenarios are defined as follows:

Scenario I – To conduct a multi-objective analysis to optimize the bicycle or MV routing in an urban area and bicycle demand at intersections;

Scenario II – To examine the impacts of volatility driving on traffic performance, emissions and safety at two-lane roundabouts.

2.2. Applied methods

2.2.1. Microscopic simulation traffic model (VISSIM)

Microscopic traffic simulation models are increasingly being applied at transportation networks to measure their effectiveness, such as delay, travel time, stop-and-go, queue length, etc. In analyzing and evaluating of traffic performance VISSIM model has been used. This preference is mainly due to sensitivity analysis, one of the VISSIM characteristics, which allows inputting various parameters represent intersection geometry and traffic data. Furthermore, because of the possibility to define different road-user behavior parameters and sub-models for different vehicle types and traffic controls.

VISSIM microsimulation model is accepted as one of the powerful tools to evaluate the different types of the roads, intersections and traffic corridors in transportation networks (Yong 2015; Fernandes et al., 2015a, 2015b) in order to assess traffic performance considering, namely: i) driving behavior parameters, such as car-following or gap-acceptance (PTV AG 2016; Fernandes et al., 2015a) ; ii) traffic lights control (fixed cycle time operation) (PTV AG 2016; Hallmark et al., 2010); iii) model calibration and validation parameters such as representation of traffic volume or travel time at each coded links (Fernandes et al., 2015a; 2017; Bahmankhah and Coelho, 2017); iv) its compatibility to integrate with micro emission models, such as VSP (Zhang et al., 2009; Fernandes et al., 2015a; 2017; Bahmankhah and Coelho, 2017); and v) its ability for sorting and exporting vehicle dynamics data in second-by-second scale (PTV AG 2016). Regarding these capability of VISSIM and also the scope of the case studies it was preferred to other traffic models.

VISSIM was developed to simulate individual vehicle movements. Calibration of VISSIM parameters was made by modifying driver behavior and vehicle performance parameters of the traffic model and examining their effect on traffic performance at each lane of the case study. Furthermore, VISSIM allows different vehicles performance such as desired maximum braking and acceleration per vehicle and class as well as to produce the requested data for the emission models (PTV AG 2016).

As described below there are some other well-known traffic software which is used worldwide for intersections, junctions and roads.

Stevanovic et al. (2009) have applied several well-known traffic micro simulators software, such as VISSIM to find the signal timing optimization effect on safety at arterial areas. In another study, the microscopic emission model, MOVESLite, is combined by VISSIM to estimate and compare the fuel consumption and emission before and after signal optimization of traffic light (Li et al., 2015). Ahn et al. (2009) chose to create microscopic simulation models in INTEGRATION and VISSIM to compare emissions produced in a signalized and stop-controlled intersection and a roundabout.

VISSIM has the ability to combine by several emission models such as MOVESLite (Li et al., 2015), VSP (Zhang et al., 2009; Fernandes et al., 2017; Bahmankhah and Coelho, 2017) and CMEM (Stevanovic et al., 2009). Moreover, the majority of the studies have integrated PARAMICS and VISSIM traffic models with CMEM or MOVES emissions models (Abou-Senna et al., 2013; Olia et al., 2016).

2.2.2. Emission estimation model (vehicle specific power - VSP)

Various studies have integrated simulated vehicle dynamic data and microscopic modeling to estimate vehicle emissions at intersections (Salamati et al., 2015), roundabouts (Coelho et al., 2006; Coelho et al., 2009; Coelho et al., 2013; Salamati et al., 2015) and roads (Zhai et al., 2008; Frey et al., 2010) in transportation networks.

According to Palacios (Palacios 1998), Vehicle Specific Power (VSP) is defined as the instantaneous power per unit mass of the vehicle. The instantaneous power generated by the engine is used to defeat the rolling resistance and aerodynamic drag, and to increase the kinetic and potential energies (KE and PE) of the vehicle. It is equivalent to the product of speed and equivalent acceleration, including the effects of roadway grade and rolling resistance, plus a term for aerodynamic drag which is proportional to the cube of the instantaneous speed.

EPA's MOVES (MOtor Vehicle Emissions Simulator), is one of the well-known emission estimation models in the United States, replaced EPA's previous emission model, MOBILE (EPA 2012). Moreover, the Comprehensive Modal Emission Model (CMEM) has been developed at the University of California to predict and measure pollutant emissions from motor vehicles (Barth et al., 2000; Barth et al., 2008). In a study conducted by Zhang et al (2009) the authors calculated the vehicle emissions ratio under different turning movements using Portable Emission Measurement System (PEMS) at intersections. In another study, Zhang and Frey (2006) found that the road grade is an important variable for emission estimation. To improve this lack of emission computations authors used the Vehicle Specific Power (VSP) emission estimation model (Frey et al., 2002).

VSP is a microscale emission model which calculates emissions based on vehicle speed, acceleration, road grade, and can be estimated engine power demand accounting for rolling resistance and aerodynamic drags (Coelho et al., 2006; Zhang and Frey, 2006). Coelho et al. (2006) used VSP methodology combined with SIDRA traffic model to evaluate the roundabout operations impact on pollutant emissions. In another study, Zhang used VSP methodology combined with VISSIM micro scale traffic simulator to evaluate the impact of alternative signal timing and traffic flow on emissions (Zhang et al., 2009).

In a similar case study in the US, VSP model is used to find the emission of selected main and alternative routes in order to find the best route which produces less emission. In this study, the details of speed and acceleration are found using a GPS system and the details have transferred to VSP model. Total emissions for each route and emission rates of operating mode bins were estimated using the operating mode binning approach provided by the MOVES model (Hoover et al., 2015). In another study that is carried out in six states of US VSP model is the base emission model for estimating and comparing the pollutant emissions generated from a roundabout and a signalized intersection (Salamati et al., 2015).

Zhai et al. (2008) have developed VSP model to evaluate roadway link average emission rates for diesel-fueled transit buses based on link mean speed. Coelho et al. (2009) have developed VSP for gasoline and diesel light duty vehicles separately based on microscale measurement.

VSP has selected as the emissions estimation model for this research since it allows estimating instantaneous emissions based on a second-by-second vehicle's dynamics (speed, acceleration and slope) and it has also been shown to be a useful explanatory variable for estimating variability in emissions, especially for CO_2, CO, NO_X and HC (Zhai et al., 2008; Coelho et al., 2009). Second-by-second vehicle activity can be characterized by VSP and modal emission factors developed from instantaneous emissions data. Furthermore, based on the literature review and several relative studies, VSP can be integrated with VISSIM for microscale analysis of road vehicles (including motor vehicles and bicycles).

The VSP values are categorized in 14 modes of engine regime, and an emission factor for each mode is used to estimate CO_2, CO, NO_X and HC emissions. Figure 2.2 depicts the VSP modes distribution for a generic Light Duty Vehicle (LDV) according with instantaneous speed and acceleration for a road grade of 0%.

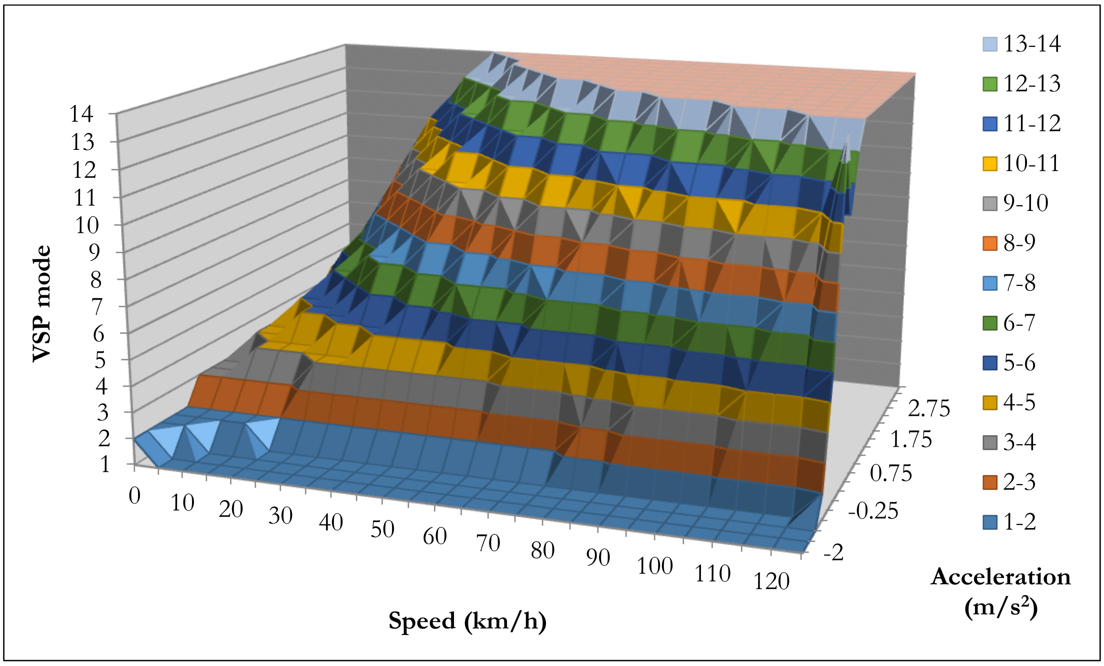

Figure 2.2. VSP modes distribution of a generic light duty vehicles for a road grade of 0%.

2.2.3. Safety model (surrogate safety assessment methodology - SSAM)

Surrogate Safety Assessment Methodology (SSAM) is a software application that reads trajectory files generated by microscopic simulation programs and calculates surrogate measures of safety (Vasconcelos et al., 2014). SSAM developed by the Federal Highway Administration – FHWA to safety analysis in intersections, roundabouts and roads (Gettman et al., 2003). This model has significant advantages in finding the potential safety risks before the occurrence of crashes.

In a report (Gettman et al., 2008) developed by Federal Highway Administration about SSAM, following information highlighted by the report:

The SSAM model is corresponding to analyze the interaction between vehicles (vehicle-to-vehicle) in order to find the probability of conflict events among the other identified events. After identifying the conflict and classifying them in a table for users, SSAM tries to measure several surrogate safety such as Minimum time-to-collision (TTC), Minimum post-encroachment (PET), Maximum speed (MaxS), Initial deceleration rate (DR), Maximum deceleration rate (MaxD) and Maximum speed differential (DeltaS) among others. Among the represented surrogate safety measures, following items included to this research that was analyzed by SSAM model: Minimum time-to-collision (TTC), Number of conflicts and Maximum speed (MaxS) between vehicles.

TTC value can be observed during the interaction between two vehicles on a collision route. In fact, the highest value of TTC represents more distance between two vehicles and when the distance between to vehicles increase it represents more safety. Further details about surrogate measures and SSAM characteristics can be found elsewhere. However, SSAM needs to integrate with traffic models and for some of the traffic model is not very compatible (Getmman et al., 2003).

Vasconcelos et al. (2014) have used SSAM as a tool for crashes prediction at urban intersections. In this study, SSAM was applied in two different intersections and one roundabout to evaluate and validate its application for traffic intersections in the urban network. The results indicate that, despite some limitations related to the nature of current traffic microsimulation models, SSAM analysis is an extremely promising approach to assessing the safety of new facilities or innovative layouts. In another study, So et al. (2015) have integrated VISSIM traffic model by SSAM to analyze the prediction accuracy of this model for the rural network. Fernandes et al. (2015b) used an integrated model of VISSIM, VSP, and SSAM to develop a simulation platform of traffic, emissions, and safety in order to optimize such variables in roundabouts' corridors.

The number of conflicts between vehicles has a significant relationship with the number of crashes in the urban network. It is one of the main items that help traffic engineers and managers to assess safety without the occurrence of an accident (Vasconcelos et al., 2013). Studying the number of conflicts between vehicles can lead to a better accident prediction.

2.2.4. Experimental measurements

The most important parameters that were considered to collect for this research were: bicycle and MVs volumes; origin-Destination Matrices; site geometry; bicycle and MVs dynamic data; driver and cyclist behavior patterns; cycle time and phasing for intersections and overtaking lateral distance.

Data collection was performed at different case studies such as distinct routes, two-lane roundabouts, signalized intersections and traffic lights were evaluated for the purposes of the thesis. Approximately 45 hours of video records and 160 km of data collection were analyzed for this thesis using different fixed and movable cameras, Global Positioning System (GPS) data logger, On-Board Diagnostic (OBD) system, 5 different gasoline and diesel vehicles (1.5<LDGV<2.5l) and a bicycle with a platform of sensors in order to measure the overtaking lateral distance between the bicycle and motor vehicles. The GPS and OBD-II used in data collection was explained in **Table 2.1** and **Table 2.2**, respectively.

Table 2.1. Global Position System (GPS)* specifications.

General		**Accuracy (none DGPS)**	
GPS Chip	MTK II GPS Module	Position	Without aid:3.0m 2D-RMS < 3m CEP(50%)without SA(horizontal) DGPS (WAAS, EGNOS, MSAS) : 2.5m): 2.5m
Frequency	L1. 1575.42 MHz	Velocity	Without aid: 1.0m/s, DGPS(WASS, EGNOS, MSAS): 0.05m/s
C/A Code	1.023MHz chip rate	**Time**	50 ns RMS
Channels	66 CH pertomance tracking	Datum	WGS-84
Antenna (Internal)	Built-in patch antenna with LNA	**Dynamic Conditions**	
Sensitivity		Altitude	<18,000m
Tracking – 165 dBm		Velocity	<515m/sec
Acquisition Rate		Acceleration	<4g
Cold start	35 sec, average	Update	1Hz as default (1~5Hz changeable by software utility)
Warm start	31 sec, average	**Interface**	
Hot start	1 sec, average	Bluetooth	V1.2 compliant (SPP profile)
Reacquisition	< 1 sec.		Class 2 (10 meters in open space)
			Frequency: 2.4~2.4835 GHz
Power		Power On/Off	Slide switch (Off-Nav-Log)
Built-in rechargeable Li-ion battery		Power charge	Mini USB
Input Voltage	Vin: DC 3.0-5.0V	**GPS Protocol**	
Backup Voltage	DC 1.2 ± 10%	NEMA-0183 (V3.01) – GGA, GSA, GSV, RMC(defult); VTG, GLL(Optional), Baud rate 115200 bps, Data bit : 8, stop bit : 1 (Defult)	
Charging Voltage	3hrs. (Typical)		
Operating temperature	-10 ℃ to + 60 ℃	**Functionality**	
Storage temperature	-20 ℃ to + 60 ℃	Beeper notice	Time Schedule
Charging	0 ℃ to + 45 ℃	Vibration sensor	Speed Alarm
Accessories		**Device Size**	
Car Charger	USB cable	72.2 (L) ×46.5 (w) × 20 (H) mm	
Rechargeable Battery	English Quick Guide	**USB Bridge**	

		Standard	Fully Compliant with USB2.0/Full speed 12Mbps

Legend: more information more information can be found here: http://www.qstarz.com/Products/GPS%20Products/BT-Q1000XT-S.htm

Table 2.2. On-Board Diagnostic (OBD) specifications.

General	
Operating Temperature	-40° to +185°F (-40° to +85°C)
Primary Power, Connected to Vehicle	9 to 16 VDC, 80 mA with vehicle running, 17 mA with the vehicle's power off
Primary Power, Connected to Computer	USB powered
Backup Power	Internal battery, minimum of 5 years total, with data logger not powered by vehicle or computer; 10-15 year life in normal use
Memory	512KB
Data Logging Capacity	300 hours maximum, depending on logging intervals and number of optional parameters selected
Time & Date	Accurate to +/- 2 seconds per day
Mounting	16-pin OBD II connector
Computer Interface	USB
Computer Cable Length	4' (1.2 m)
Alarm	Adjustable, audible alarm for exceeding speed, acceleration, and deceleration limits, when enabled in software
Status LED	LED, flashes to indicate CarChip status, when enabled in software
Dimensions	1.80" x 1.00" x 1.32" (46 mm x 26 mm x 34 mm)
Weight	0.7 oz. (20.5 g)
Software System Requirements	
Operating System	Windows XP, Vista®, 7
Disk SpaCarChip Proce	5 MB free disk space
Display	Windows-compatible VGA minimum, 800 x 600 resolution
Data Options	
Supported Unit Systems	U.S., Metric, S.I., Custom (mix of U.S., Metric, and S.I.)
Vehicle Speed Logging Interval	1, 5, 10, 20, 30 or 60 seconds
Other Parameter Sampling Intervals	5, 10, 20, 30, or 60 seconds
Vehicle Speed Bands	4 user-configurable bands identify normal vs. excessive vehicle speeds
Calculated Data	Hard and extreme braking, hard and extreme acceleration
Number of Optional Engine Data Parameters	23 total possible as supported by vehicle, up to 4 can be selected at a time
CarChip Pro Parameters	

Parameter	**Range**	**Resolution**
Vehicle Speed	0 to 158 mph, 0 to 255 km/h, 0 to 70 m/s	0.6 mph, 1 km/h, 0.3 m/s
Trip Distance Traveled	0 to 10,000 miles, 0 to 16,000 km	0.1 mile, 0.1 km

Acceleration/Deceleration Threshold	0 to 3 G, 0 to 30 m/sec^2	0.03 G, 0.3 m/sec^2
Engine Speed	0 to 16,384 rpm	1 rpm
Throttle Position	0 to 100%	0.1%
Coolant Temperature	-40° to +420°F, -40° to +215°C	2°F, 1°C
Engine Load	0 to 100%	0.1%
Air Flow Rate	0 to 8714 lb/min, 0 to 655.35 gm/sec	0.1 lb/min, 0.01 gm/sec
Intake Air Temperature	-40° to +420°F, -40° to +215°C	2°F, 1°C
Intake Manifold Pressure	0 to 75 in. hg., 0 to 255 kPaA	0.3 in. hg., 1 kPaA
Fuel Pressure	0 to 110 psiG, 0 to 765 kPaG	0.5 psiG, 3 kPaG
O_2 Sensor Voltage (up to 8 monitored)	0 to 1.275 V	0.005 V
Ignition Timing Advance	-64° to 63.5°	0.5°
Short Term Fuel Trim (up to 2 monitored)	-100% to 99.22%	0.8%
Long Term Fuel Trim (up to 2 monitored)	-100% to 99.22%	0.8%
Battery Voltage	6 to 16 VDC	0.01 VDC

Legend: more information more information can be found here: https://www.davisinstruments.com/product_documents/drive/spec_sheets/8226_SS.pdf

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3. CYCLING AT INTERSECTIONS: A MULTI-OBJECTIVE ASSESSMENT FOR TRAFFIC, EMISSIONS AND SAFETY

This chapter evaluated in an integrated manner the traffic performance, pollutant emissions and road conflicts between bicycles and motor vehicles at a signalized intersection. Two alternative scenarios were examined: (i) Bicycles increment and motor vehicles replacement within the cycle-fixed traffic signal; (ii) Replacing the existing traffic control by a conventional two-lane roundabout and evaluating the impacts of bicycles increment. For each scenario, bicycle demand was varied from 9 to 270 bicycles per hour. Traffic flow and vehicle dynamic data were collected from a three-leg signalized intersection in Aveiro, Portugal. The microscopic traffic model (VISSIM) paired with an emission (Vehicle Specific Power – VSP) and safety (Surrogate Safety Assessment Methodology – SSAM) models were used to assess intersection-specific operations. The Fast Non-Dominated Genetic Algorithm (NSGA-II) was used to find the optimal bicycle demands. The results showed that two-lane roundabout outperformed the existing traffic control (number of stops and travel time reduced in 78% and 14%, respectively; 7.0%-12% less emissions, depending on the pollutant). It was also found that the number of conflicts was significantly reduced (-49%) with this latter layout even in maximum bicycle demand scenario (270 bicycles per hour). Furthermore, the results of multi-objective analysis delivered an optimal bicycle demand lower than 165 bicycles per hour taking both environmental and safety points of view.

3.1. Introduction and objectives

Cycling demand is increasing every day, notably in high density areas (Pucher and Buehler, 2008). Cycling offers some important financial, health and social benefits to the users and environment. Bicycle is one of the most important alternatives to motor vehicle, and for short distances might be the best alternative to go easy and fast when the vehicles have to stop because of traffic congestion. They are often quicker than motor vehicles over short distances of up to 5 km (TMR 2016). Because of this reason the rate of cycling in European small cities is more than big cities (Pucher et al., 2011).

Signalized intersections are essential traffic control treatments that provide safe and efficient control of traffic congestion (Nguyen et al., 2016). Due to the complexity of intersections, the interactions of vehicle-to-vehicle and bicycle-to-vehicle increased, which means higher risk for motor vehicles and bicycles crashes at intersections, compared to other areas in urban network (Götschi et al., 2016). Almost more than half of the bicycle and motorcycle crashes and the majority of bicycle fatalities involving motor vehicles occurred at intersections (Haworth and Debnath, 2013).

Frequently reviewing traffic performance at intersections in order to find a compatible signal operation is one of the ways of improving traffic performance where the results of the review may have great impact on the energy consumption, pollutant emissions, and safety. A shorter cycle length may result in poor progress while a longer cycle length may result in excessive delays and queue blockage problems (Ramadurai 2015). Moreover, by reducing the level of congestion at intersections the number of cyclists can be increased regarding the existent negative correlation between intersection density and probability of cycling at intersections (Kaplan et al., 2016).

According to a research about bicycle and motor vehicles crashes that was conducted by Haworth and Debnath (2013) in Australia, 74.4% of bicycle crashes occur at intersections with no traffic control while the percentage of bicycle crashes at intersections with traffic lights is 18.6%. It shows that intersections with traffic lights have represented better performance in reducing driver failure that leads to cyclist crashes in comparison with unsignalized intersections. Furthermore, 80% of Australian bicycle fatalities involved motor vehicles while 58% of motor vehicles fatalities involved other motor vehicles (Haworth and Debnath, 2013).

Number of conflicts between vehicles has significant relationship with the number of crashes in urban network. It is one of the main items that helps traffic engineers and managers to assess safety and to predict accidents without occurrence of accidents (Van Hout et al., 2008). Regarding the probable safety concerns associated with the number of conflicts between motor vehicles and cyclists, roundabouts and intersections with traffic lights and stop-controlled junctions are the critical traffic points (Kaplan et al., 2016). The potential conflicts between vehicles and cyclists at these uninterrupted traffic flow can be more significant in areas where cycling activity is expected. Regarding safety, the study of conflicts between bicycle and motor vehicle might be more important than conflicts between motor vehicles since cyclist have more vulnerable potential and exposed to damage of a collision than motor vehicles’ drivers (Götschi et al., 2016).

The analysis of traffic signals impact on traffic performance and emissions is extensive. The first studies, which date back to the 1970s, focused on the traffic performance and emissions impacts at intersections and can be found in the Environmental Protection Agency (EPA) reports (Frey et al., 2002). Since then a lot of related studies have been performed both in a macroscale and microscale levels. For instance, on a microscale level, there have been several studies about the impact of signal optimization (Zhang et al., 2009; Khaki et al., 2014), Level-Of-Service (LOS) improvement (Hurley and Kalus, 2007; Barth and Boriboonsomsin, 2008; Papson et al., 2012; Mok et al., 2013), and situation of emissions generated by vehicles at intersections (Coelho et al., 2005; 2006; Li et al., 2011; Zhou and Cai, 2014).

There were several studies focused on impacts of cycling regarding safety concerns, traffic performance and emissions at intersections [about traffic performance-safety: (AlRaji 2015; Huang et al., 2013) and about traffic performance-emissions: (Zhang et al., 2009; Khaki et al., 2014; Zhou and Cai, 2014)]. However, there is a lack of research about impacts of cycling at intersections using multi-objective analysis in order to find the balanced solutions regarding safety, emissions and bicycle demand at intersections. The multi-objective studies in traffic engineering have been using optimization methods (Stevanovic et al., 2015) but little is known about the impact of bicycles at intersections on traffic performance, emissions and safety in an integrated way. Stevanovic et al. (2015) have used multi-objective analysis to evaluate the traffic signal operation integrated impacts on three dimensions; traffic performance, emissions and safety at signalized intersections but the main focus of research was based on motor vehicles, not including bicycles.

The presence of bicycles may dictate a trade-off in the network. On one side, as the number of cyclists increases, the emissions generated by vehicles (assuming a same traffic demand) and the number of traffic conflicts increases. On the other side, the severity of conflicts tends to be high with low demand of bicycles because vehicles are able to attain high speeds. Since the existing trade-off between the results are associated with different performance measures, the multi-objective analysis can be useful and informative (Bai et al., 2011).

Since most of bicycle fatalities involve motor vehicles, studying the interaction between vehicles and specially bicycles-vehicles can help to a better accident prediction in urban areas. Also, a deeper understanding of the different levels of analysis (traffic performance, emissions and safety) is needed to find the optimum balanced points regarding to safety and emission concerns, and bicycle demand. This paper addressed above concerns in a real-world urban three-leg signalized intersection with vary levels of bicycles demand, and evaluate the safety of cyclists, traffic performance and global and local pollutant emissions.

Thus, the main objectives of this paper are:

- To evaluate the impact of increasing bicycle demand on traffic performance, global and local pollutant emissions and safety;
- To improve site-specific operation by proposing a different traffic control treatment (two-lane roundabout instead of traffic lights) for the intersection;
- To conduct a multi-objective analysis to find optimum bicycle demands to improve site-specific emissions and safety.

3.2. Methodology

The present work uses a microscopic simulation platform of traffic (VISSIM) (PTV 2011) and emissions (Vehicle Specific Power – VSP) (Frey et al., 2002) to analyze traffic operations and to estimate carbon dioxide (CO_2), nitrogen oxides (NO_X), carbon monoxide (CO), and hydrocarbons (HC) emissions generated by vehicles. Also, the Surrogate Safety Assessment Methodology (SSAM) was applied to estimate conflicts from vehicle-vehicle and vehicle-bicycle interactions and to compute surrogate safety measures. The Time-to-Collision (TTC) and the minimum Post-Encroachment Time (PET) were used to assess conflict severity, and the initial Deceleration Rate (DR), maximum speed (MaxS) and maximum relative speed difference (DeltaS) during the conflicts used to represent the severity of the potential crashes. The intersection lanes operation was videotaped and necessary data were extracted from these tapes. Also, a test-equipped vehicle with a Global Position System (GPS) collected second-by-second speed and acceleration-deceleration rates. Subsequently, the collected data were coded in VISSIM after calibration and validation. The flowchart of methodology was illustrated in **Figure 3.1.**

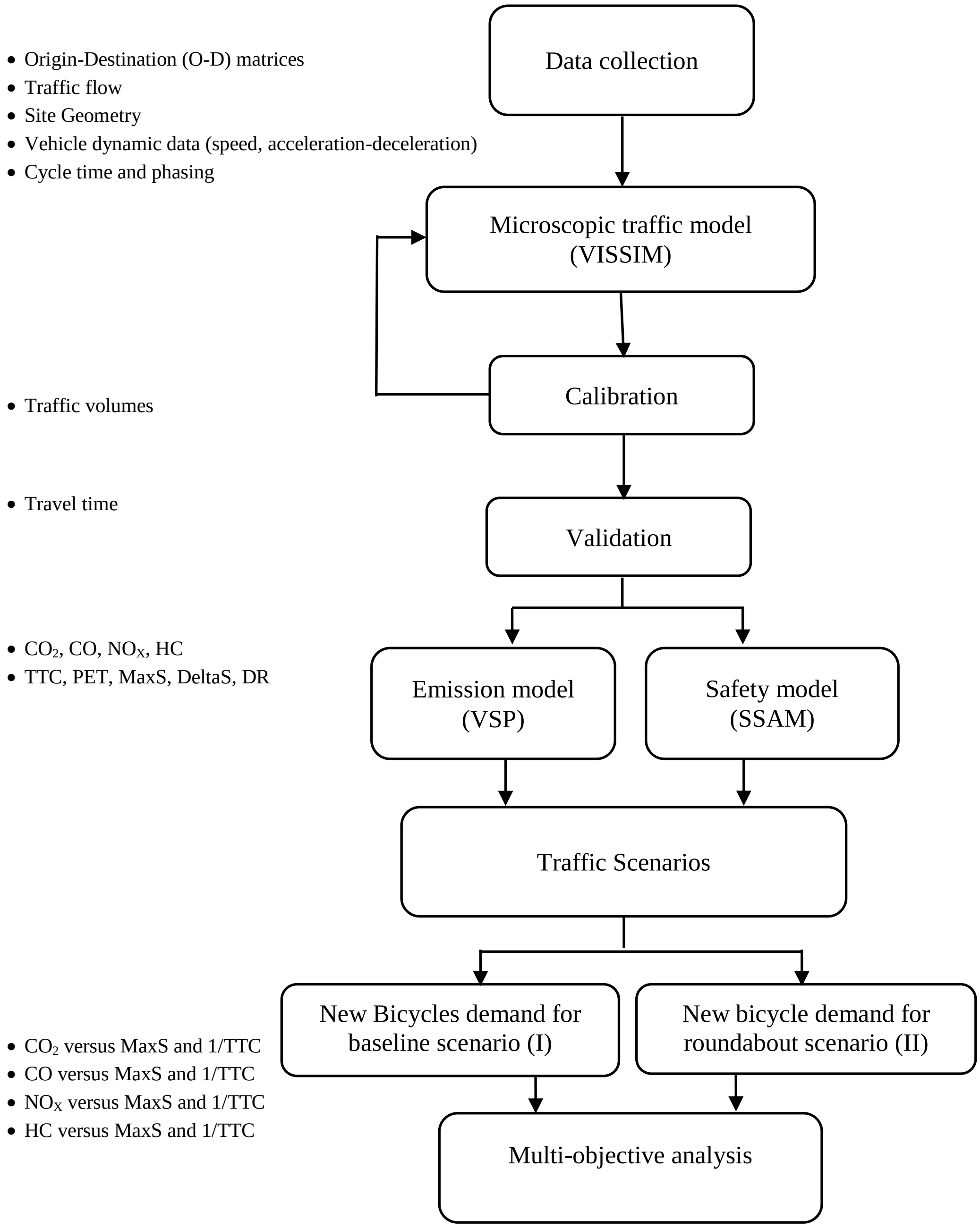


Figure 3.1. Methodological framework.

3.2.1. Site selection and field data collection

The case study is a three-leg intersection controlled by traffic light located in the city of Aveiro, Portugal. It has potential traffic conflicts caused by left-turning vehicles from North to East directions. The segments that were considered to monitor traffic volumes included 300 m upstream the traffic light, as shown in **Figure 3.2**.

The camera was placed near the intersection, approximately 5 m above the ground, on the pedestrian bridge over the main road Traffic signal is working based on fixed time operation with two-phases and the cycle time is 80 s. In Phase-I, there are two protected turns, without opposing vehicular flow, to right and left for minor lane (diverting conflict) while in phase-II there are different types of conflicts (diverting, major and merging) for the major lane of the intersection. All the data were collected on three typical weekdays (Tuesday to Thursday), at morning peak hours, from 8:30 a.m. to 9:30 a.m.

The average traffic volume was 1,649 vehicles per hour (vph) and 9 bicycles per hour (bph). Furthermore, the operation of signal time represents 40s green interval, 3 s yellow interval and 37s red interval for first phase that is the cycle time related to the major lanes (North and South directions).

Considering the major lane, during Phase-I vehicles experience two diverting and two major conflicts but, about minor lane, during the phase-II vehicles can experience only two diverting conflicts (**Figure 3.2** and **Figure 3.3**). For example, from minor lane vehicles can pass the intersection by turning to South and North when the signal is red for the major lane. The vehicles from major lane can pass the intersection by keeping the straightway from North to South or South to North (two major conflicts) and also by turning from major lane to minor lane (two diverting conflicts). The video tapes from the study site were observed to analyze the observed conflicts data. Equipped light duty vehicle performed several trips at the major roads (mainly North-South and South-North movements). A GPS data logger was installed in a test-vehicle to record vehicle speed, distance travelled, and deceleration-acceleration rates in 1-second interval. 100 GPS travel runs were extracted and identified for this research. These runs were performed during morning peak period in April 2016, from 7 a.m. to 10 a.m., and under dry weather conditions.

Figure 3.2. Layout of the case study with the identification of videotaping and traffic lights. (Source: http://www.bing.com/maps/)

3.2.2. *Traffic modelling*

VISSIM software package was selected to simulate traffic operations (PTV 2011). The capability of VISSIM model in reproducing accurately traffic and bicycle operations at microscale for intersections is one of the main advantages of this traffic model (Mok et al. 2013; AlRaji 2015).

All simulation experiments were made for the analysis period between 8:20 p.m. and 9:30 p.m. with a 10-minutes “warm-up” period prior to 8:30 p.m. to load the study domain adequately with corresponding traffic flow.

3.2.3. *Emissions estimation*

The selected methodology to estimate the emissions is based on the concept of Vehicle Specific Power (VSP). The scope of analysis is focused on vehicular emissions of CO_2, NO_X, CO, and HC. VSP is estimated from a second-by-second speed profile based on emission factors from typical Light-Duty Vehicles (LDVs) (Frey et al., 2002). Furthermore, VSP is associated with any speed trajectory and has capability to estimate the footprint of emissions at intersections with traffic lights and roundabouts (Coelho et al., 2006; Salamati et al., 2013; Salamati et al., 2015). Eq. 1 provides the generic VSP equation from typical LDVs (Frey et al., 2002):

$$\text{VSP} = v.\,[1.1\,a + 9.81\,(a.\tan(\sin(\text{grade}))) + 0.132] + 0.000302v^3 \quad (1)$$

Where VSP is vehicle specific power (kw/metric ton); v is the instantaneous speed (m/s); a is the acceleration/deceleration rate (m/s^2); and grade is road grade (decimal fraction).

Each VSP bin refers to one of 14 modes. Each VSP mode is defined by a range of VSP values which are associated to an emission rate. Each calculation of VSP results in a unique classification to a VSP mode (Anya et al., 2013; Coelho et al., 2009).

The following fleet composition based on the Portuguese car fleet distribution (ACAP 2014) was considered: 44.7% of light duty gasoline vehicles, 34.3% of light duty diesel vehicles and 21.0% of light commercial diesel vehicles. Other categories (transit buses and heavy duty trucks) represented only 1% of traffic composition and were excluded from the emissions calculations. Because the terrain is flat, the effect of the slope was ignored.

3.2.4. Safety model

For the safety assessment approach the software developed by the Federal Highway Administration - FHWA (Surrogate Safety Assessment Model – SSAM) was used (Gettman et al., 2008).

Traditionally, traffic safety assessment heavily relies on crash data analysis, in which the number or consequences of crashes were used as measures of effectiveness to evaluate the safety performance of traffic facilities (Huang et al., 2013). SSAM automates traffic conflict analysis by processing vehicles trajectories from a microscopic traffic model as is the case of VISSIM. For each simulation, SSAM stores the trajectories of vehicles and bicycles from the traffic model and determines whether or not an interaction between vehicle-to-vehicle or vehicle-to-bicycle satisfies the condition to be deemed a traffic conflict (Fernandes et al., 2015). The authors used the Time-to-Collision (TTC) as a safety indicator to assess whether a vehicle-vehicle and vehicle-bicycle interaction can result in conflict. If at any time the TTC drops below 1.5 s, the interaction is tagged as a conflict. TTC is a measure of conflict severity (low values of TTC indicate high severe conflicts).

Also, the research team used the minimum Post-Encroachment Time (PET) to assess conflict severity, and the initial Deceleration Rate (DR), maximum speed (MaxS) and maximum relative speed difference (DeltaS) during the conflict to represent the severity of the potential crashes (Gettman et al., 2008). It must be mentioned that SSAM classifies resulting conflicts into three categories based on a conflict angle (from -180° to +180°): rear end if 0º < conflict angle <30°, a crossing conflict if 85º < conflict angle < 180°, otherwise is a lane change conflict (Gettman et al., 2008).

3.2.5. Alternative scenario

In order to improve traffic operation and safety levels, two alternative scenarios were presented based on the potential role of bicycles:

Scenario I – Increasing number of bicycles from 9 to 270 with 30-bph increments for baseline scenario and replacing number of motor vehicles based on occupancy ratio of motor vehicles (1.2 person per 1 motor vehicle) for each volume of bicycle demand (Schultz et al., 2015). It should be noted that, increasing the number of bicycles and replacing the motor vehicles was done based on their distribution rate at each lane of the network. This range of values was justified by the new project implementation (U-Bike 2016) that aims to encourage as many people as possible to use the bicycle as a regular transport mode, and as a result 240 new bicycles will be provided at campus area of the University of Aveiro. Furthermore, assuming 30 more active bicycles for current situation the impact of new situation was analyzed up to 270 bph.

Scenario II – The existing traffic control was replaced by a two-lane roundabout and evaluating the impacts of new bicycles increment as same as the first proposed scenario. The number of bicycles increased for proposed roundabout and the number of motor vehicles replaced based on occupancy ratio between bicycle and motor vehicle, as it was defined before, for each volume of bicycle demand. The roundabout layout was built according the Portuguese Guidelines (Bastos and Seco, 2012): inscribed circle diameter = 43.8m and circulating lane width = 7.9m. The entries and exits of the northbound and southbound lanes have two lanes while eastbound road has one lane in both directions.

3.2.6. Multi-objective optimization

The Fast Non-Dominated Genetic Algorithm (NSGA-II) was applied to conduct the multi-objective analysis (Moussouni et al., 2007). NSGA-II was reported as one of the effective algorithm in finding a good approximation of an optimal Pareto front (Konak et al., 2006).

This algorithm is one of the popular genetic algorithms with high optimization quality ability for several multi-objective problems studies (Chakraborti et al., 2008). Its particular fitness assignment scheme consists in sorting the population in different fronts using the non-domination order relation. Then, to form the next generation, the algorithm combines the current population and its offspring generated with the standard bimodal crossover and mutation operators. Finally, the best individuals in terms of non-dominance and diversity are chosen (Moussouni et al., 2007).

Among the safety indicators the TTC and MaxS were selected to represent the severity of conflicts and collision respectively. Moreover the global and local emissions were selected to analyze against these safety indicators to find the existent differences between them.

The following multi-objective tests were performed: a) CO_2 versus MaxS; b) CO_2 versus 1/TTC; c) CO versus MaxS; d) CO versus 1/TTC; e) NOx versus MaxS; f) NOx versus 1/TTC; g) HC versus MaxS; h) HC versus 1/TTC. Once these tests perform, the optimal bicycle data set values were obtained for each case. A set of 15 optimal solutions was considered for this analysis. In addition, all objective variables are considered to have the same weight during the optimization procedure.

3.3. Results and discussion

3.3.1. Traffic and safety model calibration and validation

VISSIM traffic model was first calibrated to reproduce site-specific traffic flows. Thus, driver behavior parameters of VISSIM traffic model were adjusted with the main purpose of assessing their impact on traffic volumes for each coded link. The calibrated driver behavior measures included the car following – average standstill distance, additive and multiple part safety distance; gap acceptance – visibility, front and rear gaps and safety distance; and lane change – waiting time before diffusion, min-headway, safety distance reduction factor and maximum distance for cooperative breaking. The modified chi- squared statistics Geoffrey E. Havers (GEH) that incorporates both absolute and relative differences in comparison of estimated and observed volumes, was used as the calibration criteria (Buisson et al. 2014). In this case, 85% of the links must meet the GEH value lower than 4. In addition, the Mean Absolute Percent Error (MAPE) was used to measure the size of the error (deviation) for the observed and estimated traffic volumes.

Data collected from the selected intersection were used to calibrate and validate the simulation model. Calibration of VISSIM parameters was made based on estimated and observed traffic volumes with 15 random seed runs (Hale 1997). A good fit between observed and estimated data was obtained ($R^2 = 0.99$) using a linear regression analysis. It was found that all the 36 links recorded a GEH value lower than 4 which satisfied the calibration criteria proposed by Dowling et al. (2004), while MAPE values were lower than 4%.

Regarding model validation, a comparison of observed and simulated travel time at the two main lanes of intersection, for North-South and South-North movements, was conducted using 100 floating car runs (Dowling et al., 2004). Observed travel time were obtained by vehicle dynamic data collected from through movements (North-South and South-North) at major lanes while simulated travel time came from vehicle record tool of VISSIM traffic model (PTV 2011). The difference between observed and estimated average travel time was not statistically significant at a 5% significance level. This demonstrated the accuracy of the traffic model in representing intersection-specific operations.

Regarding the type of intersection, the three hours recorded videotapes were later reviewed for several times in order to obtain the traffic conflicts to record the information associated with each conflict (Huang et al., 2013), as shown in **Figure 3.3**. The authors ran VISSIM simulation model for three hours and the results classified with 15-min time intervals. In order to be consistent with the conflict types used in SSAM, the observed conflicts were classified into three types: (a) Rear-end conflicts, (b) Lane-change conflicts, and (c) Crossing conflicts.

Linear regression analysis was conducted to identify if the simulated traffic conflicts provided reasonable estimates for the observed traffic conflicts. Linear regression models were fitted to relate the simulated conflicts to total observed conflicts in the site. It was found that the relationships between the simulated and the observed conflicts were statistically significant and acceptable (**Figure 3.3**).

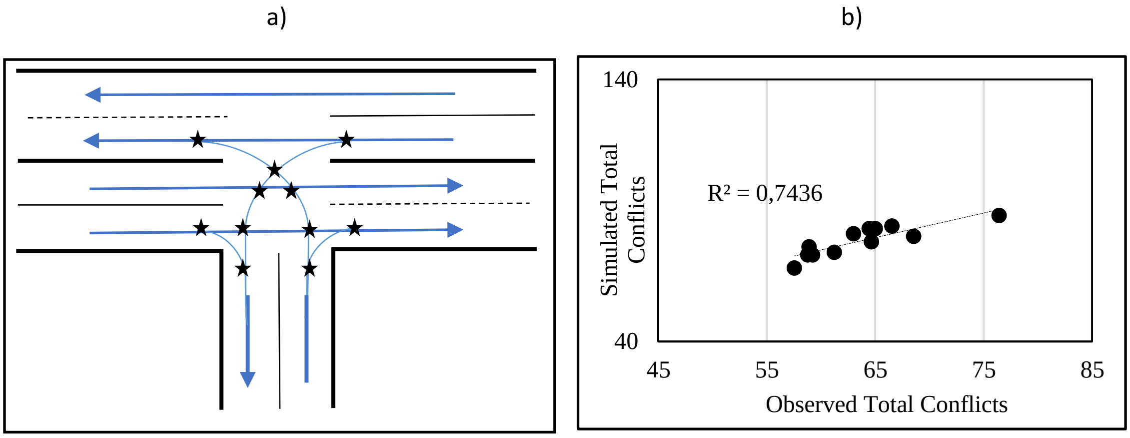


Figure 3.3. a) Conflict types observed at three-leg signalized intersection; b) Relationship between observed and simulated conflicts.

3.3.2. Baseline and alternative scenario – I

This section presents the main results for baseline and alternative scenario I. Average vehicle travel time and number of stops were given from the vehicle record tool of VISSIM model (PTV 2011) while TTC, PET, MaxS, DeltaS and DR were computed in SSAM (Gettman et al., 2008).

Table 3.1. lists traffic performance, emissions and safety outputs for above scenarios by bicycle demand scenario. As the number of bicycles increased from 9 to 270 bicycles, the emissions generated by vehicles reduced (on average 9%, 6%, 6% and 8% for CO_2, CO, NO_X and HC) and concomitantly the travel time increased about 5% for the motor vehicles. This happens because, although there are less vehicles in the network but these are more impacted by cyclists and so they spend more time, individually in the road.

The bicycles did not follow the same trend. Due to bicycles increment at the study domain, the number of stops increased from 4 (9 bph) to 148 (270 bph), and the travel time increased from 94.1 seconds to 105.5 seconds respectively as well. The increase in the number of bicycles resulted in more conflicts (27% more in the 270 bph scenario compared to the existing condition). In terms of safety, since there is no stable trend in TTC and PET values, it is not possible to conclude an explicit result when bicycle demand increased. The severity of potential collisions increased as MaxS point of view, but DR (in absolute terms) and DeltaS did not vary among different bicycle demand scenarios.

Table 3.1. Summary results of baseline and alternative Scenario – I

Vehicles	**Pollutants**	**Scenarios**									
		Baseline 9 bicycles (bph)	**Alternative - I**								
			30 bicycle (bph)	60 bicycle (bph)	90 Bicycle (bph)	120 bicycle (bph)	150 bicycle (bph)	180 bicycle (bph)	210 bicycle (bph)	240 bicycle (bph)	270 bicycle (bph)
MOTOR VEHICLES	CO_2 (kg)	173	172	170	170	168	162	164	162	160	158
	CO (g)	227	228	226	227	225	217	222	219	216	214
	NO_X (g)	511	512	509	510	506	487	497	491	485	481
	HC (g)	8.5	8.4	8.3	8.3	7.9	8.1	8.0	7.9	7.8	7.8
	CO_2 (g/km)	260	263	264	268	270	269	273	274	277	279
	Stops (n)	928	853	822	814	817	775	795	795	782	782
	Travel time (s/veh)	48.1	48.1	48.1	48.7	49.7	49.0	49.6	50.0	50.2	50.6
	Speed Avg (km/h)	44.5	44.1	44.0	43.8	43.4	43.1	42.7	42.5	42.4	42.0
BICYCLES	Stops (n)	4	15	29	48	67	84	102	112	133	148
	Travel time (s/veh)	94.1	102.8	100.7	103.2	104.1	103.1	103.8	104.4	105.0	105.5
	Speed Avg (km/h)	20.0	19.8	20.0	19.8	19.6	19.6	19.5	19.5	19.3	19.3
SAFETY	Conflicts(n)	81	82	86	86	92	92	96	98	98	103
	TTC (s)	1.14	1.17	1.17	1.14	1.15	1.13	1.14	1.14	1.13	1.14
	PET (s)	1.61	1.61	1.63	1.55	1.51	1.45	1.45	1.50	1.46	1.51
	MaxS (m/s)	6.39	6.54	6.64	7.00	6.92	7.20	7.05	7.19	7.38	7.14
	DeltaS (m/s)	5.28	5.20	5.07	5.10	4.99	5.18	4.98	4.98	4.96	4.86
	DR (m/s^2)	-2.31	-2.37	-2.35	-2.46	-2.38	-2.45	-2.45	-2.44	-2.44	-2.33

3.3.3. Alternative roundabout scenario – II

The findings confirmed some improvements on traffic performance and emissions using two-lane roundabout, as presented in **Table 3.2.** The results showed that in the first demand (30 bph) the emissions in CO_2, NOx and HC, reduced 1.2%, 0.6%, and 3.5% respectively, compared to traffic light solution (baseline). However, CO emissions were higher in roundabout scenario (2.6%), this is may be due to the acceleration and deceleration episodes that vehicles experienced in the downstream and upstream areas of the roundabout. Continuing to increase the number of bicycles, and replacing more motor vehicles as well, the reduction in emissions was more pronounced. For instance, in last demand scenario (270 bph) CO_2, NOx, and HC vehicular emissions decreased 9.0%, 7.0%, and 12% respectively. Also, roundabout solution was very effective in terms of traffic performance measures (its implementation allowed the number of stops and travel time to be reduced in more than 78% and 14%, respectively in the last demand). About the bicycles, the traffic performance measures dictated notable reduction in the number of stops while travel time did not vary after implementing roundabout.

The findings confirmed significant improvements on safety regarding the number of conflicts. The results showed that in the first demand (30 bph), the number of conflicts reduced 74%, compared to traffic light solution (baseline). Furthermore, even by increasing the number of bicycles up to 270 (last demand) the number of conflicts reduced to 49%. However, there was not a consensus about safety variables. Both TTC and PET decreased which means more severe conflicts. Notably, roundabout scenario recorded high MaxS values, especially under high-bicycle demand scenarios (on average 30% higher than those obtained in the signalized solution). This is caused by weaving maneuvers of vehicles at the circulating area of the roundabout. In summary, the benefits of roundabout layout in traffic performance and emissions measures were pronounced while the safety benefits were not so clear. In such cases, the roundabout caused more severe conflicts as the number of bicycle users increased, as well as more severe potential crashes (as MaxS criteria) compared to baseline scenario. However, the difference in surrogate measures for roundabout scenario was not statistically significant at a 5% significance level ($p\text{-value} < 0.05$). Several explanations support these results. First, most of conflicts in the baseline occurred near the traffic light and during the left-turning movements (vehicles are waiting for a crossable gap of South approach vehicles), as depicted in **Figure 3.4.** In the roundabout, the severity of conflicts can increase due to circulating area of roundabout that drivers experience moderate speed and lane change (as a presence of other vehicles or bicycles) which does not occur in the baseline scenario. The **Figure 3.4** also shows that the extent of hotspot conflicts locations is higher in scenario I than in scenario II. This is explained by the longer queues that vehicles experience due to red signal both in main roads and minor roads.

The implementation of the roundabout also was effective in eliminating the traffic conflicts at the exits of the intersection. Overall, three main conclusions can be drawn: 1) two-roundabout improved traffic performance and some pollutant emissions at the selected intersection regardless of the number of bicycle users; 2) safety benefits of this layout were less pronounced under high-bicycle demands; and 3) increasing the number of bicycle users resulted in a degradation of traffic and cyclist's operations from a certain level of demand.

With these concerns in mind, the research team decided to develop a multi-objective analysis to search the optimal number of bicycles to improve emissions and safety variables for the roundabout scenario.

Table 3.2. Summary results of alternative Roundabout Scenario – II

Vehicles	**Pollutants**	**Scenarios**										
		Baseline 9 bicycles (bph)	**Alternative - II**									
			9 bicycle (bph)	30 bicycle (bph)	60 bicycle (bph)	90 Bicycle (bph)	120 bicycle (bph)	150 bicycle (bph)	180 bicycle (bph)	210 bicycle (bph)	240 bicycle (bph)	270 bicycle (bph)
MOTOR VEHICLES	CO_2 (kg)	173	172	171	168	168	167	163	163	161	159	157
	CO (g)	227	233	233	229	229	229	225	224	222	219	217
	NO_X (g)	511	508	508	500	501	499	490	489	486	479	475
	HC (g)	8.5	8.2	8.2	8.0	8.0	8.0	7.8	7.8	7.7	7.6	7.5
	CO_2 (g/km)	260	193	195	196	198	200	201	201	203	203	205
	Stops (n)	928	107	111	106	195	197	199	200	200	202	204
	Travel time (s/veh)	48.1	39.1	39.4	39.6	39.9	40.3	40.4	40.5	47.4	41.3	41.3
	Speed Avg (km/h)	44.5	51.1	50.8	50.6	50.3	49.9	49.7	49.6	49.2	48.9	48.8
BICYCLES	Stops (n)	4	1	0	1	3	3	4	4	6	8	11
	Travel time (s/veh)	94.1	94.4	94.6	94.6	95.7	96.1	95.1	96.4	96.8	94.3	97.5
	Speed Avg (km/h)	20.0	22.2	21.8	22.3	22.4	21.6	21.6	21.6	21.4	21.4	21.3
SAFETY	Conflicts(n)	81	19	21	24	22	32	31	35	36	37	41
	TTC (s)	1.14	1.15	1.11	1.11	1.08	1.08	0.98	1.06	1.03	1.03	1.03
	PET (s)	1.61	1.40	1.23	1.30	1.13	1.18	1.03	1.08	1.04	1.06	1.05
	MaxS (m/s)	6.39	6.72	7.84	8.30	8.90	8.78	9.52	9.61	9.53	9.63	9.64
	DeltaS(m/s)	5.28	4.94	4.85	4.83	5.01	4.93	4.88	4.96	5.11	4.78	5.13
	DR (m/s^2)	-2.31	-2.17	-2.57	-2.52	-2.48	-2.44	-2.54	-2.61	-2.73	-2.60	-2.46

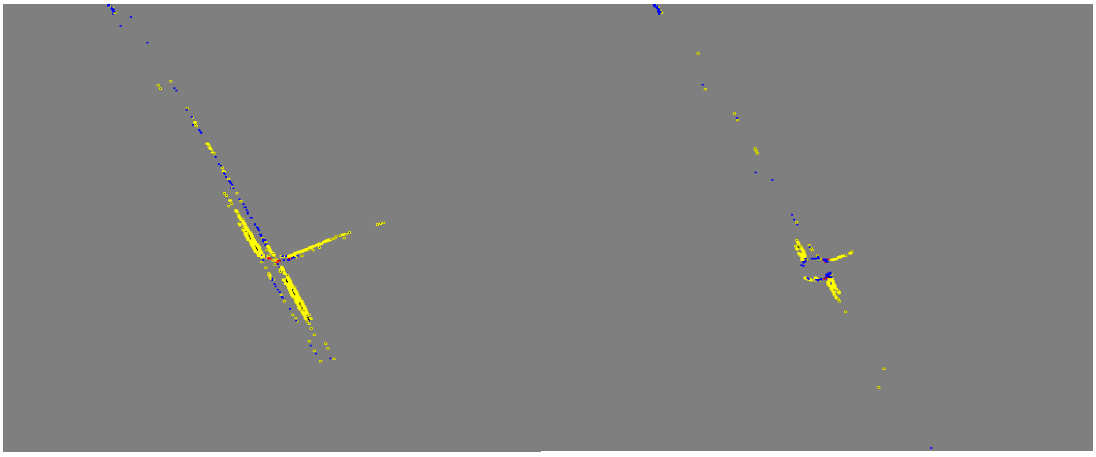


Figure 3.4. Hot Spot Conflicts location for the baseline (left) and roundabout (right) scenarios. (Crossing Conflicts – Red color, Lane Change - Blue color, Rear End - Yellow color)

3.3.4. Multi-objective optimization

This section presents the main multi-objective results for the alternative scenario. The analysis of the convergence to Pareto fronts and the diversity of solutions indicated that a maximum of 100 iterations were sufficient to reach convergence (the range of the optimal bicycle demand solutions became stable). Also, the crossover and mutation were set at 90%, and 15% respectively.

The multi-objective resulted solutions from this scenario are illustrated in **Figure 3.5** that shows the Pareto fronts estimated from final population (after 100 generations). For this scenario (II), two dimensions were CO_2, CO, NOx, and HC emissions (x-axis), and MaxS and the inverse of the TTC (y-axis) were drawn based on bicycles numbers. It is to be noted that the unit of TTC is defined in inverse second (s-1) because NSGA-II minimized a given function (longer TTC represents less severe conflicts). In **Figure 3.5** for each level of bicycle demand, a two dimensional Pareto frontier with two objective functions – emissions (x-axis), and safety measure (y-axis) – is defined. Data labels indicate the set of points that represent optimal solutions as bicycle demand value of the Pareto fronts. The optimal solutions, which conducted with the minimal vehicular emissions, were allocated to the upper-left, while the optimal bicycle demand values which led to the minimal conflict severity and potential crashes, was assigned lower-right. For instance, adopting a solution number 8 (bicycle demand of 74 bph), from **Figure 3.5** (a), which is closest to the abscissa of the graph will conduct to 2.3% of CO_2 decreases and 31.5% increase in MaxS, compared to traffic light solution (baseline with 9 bph). Moreover, adopting a solution number 8 (bicycle demand of 68 bph), from **Figure 3.5** (f), will be conducted to 1.8% of NO_X decreases and 4.9% increase in 1/TTC, compared to traffic light solution (baseline with 9 bph).

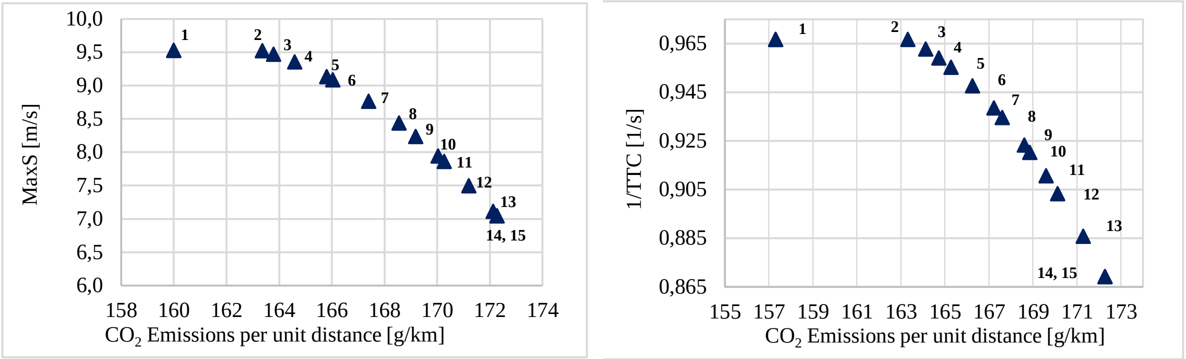
Regarding the global and local pollutants comparison between traffic light solution and the optimal data sets, the results showed that CO_2, NOx, and HC emissions decreased for all the represented optimal solutions (all bicycle demands). CO decreased for the baseline scenario when bicycle demand was more than 90 bph. For the alternative scenario all the pollutants were decreased by increasing the bicycle demand from 9 bph to 270 bph.

3.4. Conclusions

This research addressed the impact of bicycle demand at a three-leg signalized intersection on traffic performance, vehicular emissions and safety. Also, this research proposed a roundabout for the intersection and compare with the existing situation subjected to increments in the number of bicycle users (and decrease in the number of motor vehicles based on occupancy ratio). Lastly, the research improved site-specific operations by searching the optimal number of bicycle users to minimize global and local pollutants and call to optimize surrogate safety measures criteria.

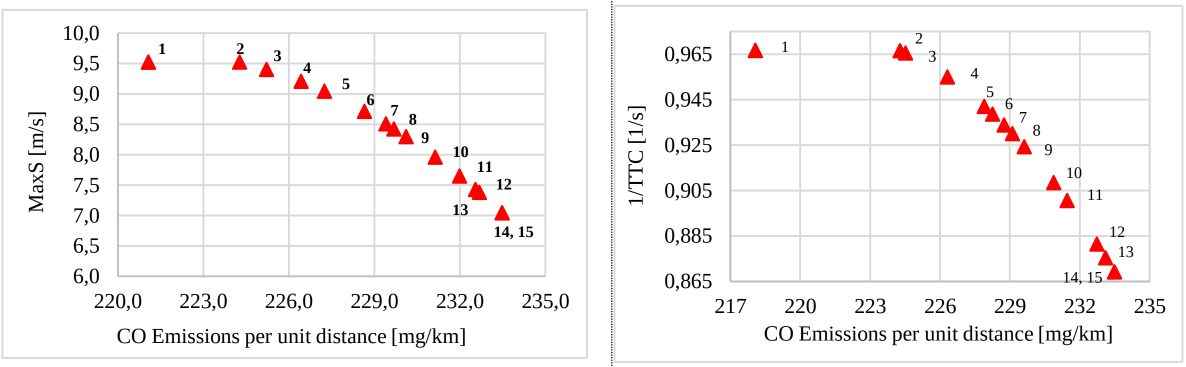
The analysis results showed a reduction in emissions (6-9%, depending on the pollutant) by increasing the number of bicycle users from 9 to 270 for signalized intersection, while bicycles' travel time increased from 94.1 s to 105.5 s. It was also found that the roundabouts outperformed signalized intersection as CO_2, NOx and HC criteria regardless of the bicycle demand scenario. The proposed layout also improved the number of vehicle stops and number of traffic conflicts, but this was not hold for surrogate measures (more severe conflicts in roundabout solution and not clear trend for potential severe crashes). Based on multi-objective analysis bicycle demand lower than 165 bph dictated a good compromise between global and local pollutants, and the inverse of TTC and MaxS safety variables. CO_2, NOx, HC and CO emissions decreased in all the represented optimal solutions (all bicycle demands) for the proposed alternative scenario.

Since this research was focused on a three-leg intersection, further studies is needed about different types of intersections before generalizing the same results of this paper for all of them.



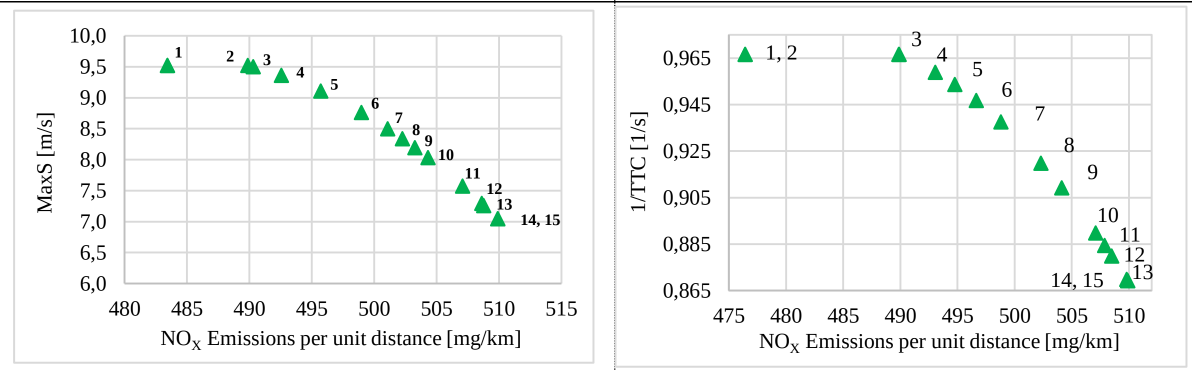
a) CO$_2$ versus MaxS

b) CO$_2$ versus 1/TTC



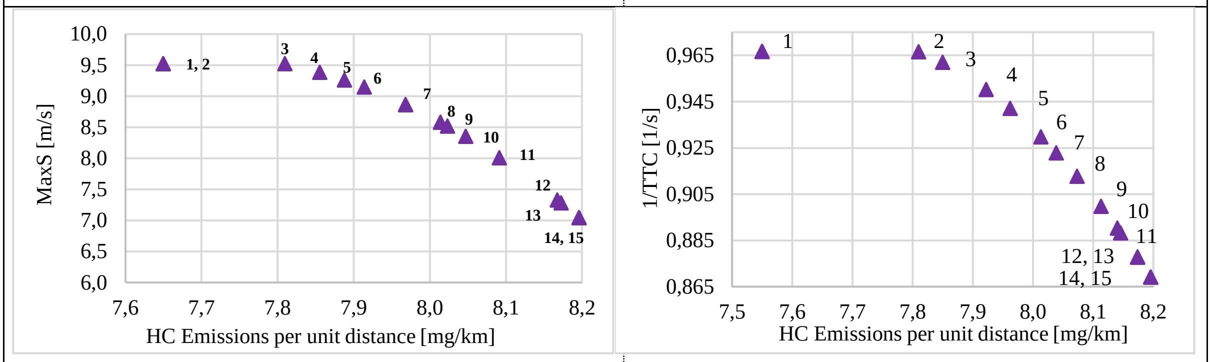
c) CO versus MaxS

d) CO versus 1/TTC



e) NO$_X$ versus MaxS

f) NO$_X$ versus 1/TTC



g) HC versus MaxS

h) HC versus 1/TTC

Figure 3.5. The approximate final Pareto front for alternative scenario II: a) CO$_2$, MaxS; b) CO$_2$, 1/TTC; c) CO, MaxS; d) CO, 1/TTC; e) NOx, MaxS; f) NOx, 1/TTC; g) HC, MaxS; h) HC, 1/TTC.

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4. MULTI-OBJECTIVE OPTIMIZATION FOR SHORT DISTANCE TRIPS IN AN URBAN AREA: CHOOSING BETWEEN MOTOR VEHICLE OR CYCLING MOBILITY FOR A SAFE, SMOOTH AND LESS POLLUTED ROUTE

Mobility in urban areas is highly complex because of the variety of possible facilities and routes, the multitude of origins and destinations, the increase of population density and traffic. Furthermore, people are willing to use more environmentally friendly transportation modes, such as cycling, to do short-distance trips in urban areas.

This chapter develops a multi-objective model for passengers in urban transportation network for short trips using bicycle or motor vehicle. The main objective of this paper is to improve the urban network mobility in order to decrease traffic congestion, road conflicts between road users and pollution. Furthermore, optimization objectives could comprehensively reflect expectations of passengers from the dimension of traffic and emissions as criteria and use a motor vehicle or a bicycle as an alternative. After getting the results the methodology was examined the role of dedicated lane for bicycle to show the differences between the results with and without considering this lane at case study.

Furthermore, PC-Crash software was conducted to simulate the safety of cyclist at selected case study before implementing the dedicated lane for bicycle.

The methodology of this study was applied based on the real world case study in the city of Aveiro, Portugal. The present work uses a microscopic simulation platform of traffic (VISSIM), road safety (SSAM), and emissions (Vehicle Specific Power – VSP) to analyze traffic operations, road conflicts and to estimate carbon dioxide (CO_2) and nitrogen oxide (NOx) emissions. Three-dimensional Pareto Fronts, which were expressed through traffic performance, road conflicts between motor vehicles and bicycles and emissions, were optimized using the fast Non-Dominated Genetic Algorithm (NSGA-II).

4.1. Introduction and objectives

Cycling brings the following advantages: health issues improvement, environmental preservation, and lower traffic congestion. Hence, the demand for cycling increases day after day especially in high density areas (Pucher and Buehler, 2008; Twaddle et al., 2014; Coelho and Almeida, 2015). Because of complexity and congestion characteristics of urban road networks, to cycle can be defined as the best and fast alternative to use in a group of multiple roads. The short distance variety of routes between origin and destination gives more alternative to the cyclist when compared to the user of a motor vehicle; under a considerable variety of options, bicycle users may choose the optimal route according to their personal preference such as travel time, emissions and safety concerns.

Considering safety, in case of urban areas, number of conflicts has a significant relationship with the number of crashes (Van Hout et al., 2008). Moreover, traffic safety concerns could be of high importance for cyclists due to the fact that a bicycle has more vulnerable potential and exposed to damage of a collision than a motor vehicle (Van Hout et al., 2008; Götschi et al., 2016).

The problem of air pollution in urban areas is aggravated and becoming a critical issue in terms of increased emissions. European Environment Agency (EEA) estimates that air pollution causes 467,000 premature deaths a year in Europe (EEA 2016).

Due to these reasons it appears that not only traffic performance but also vehicle emissions and safety concerns appear simultaneously as key challenges in urban road networks. In this way the role of bicycle can be more important because increasing the modal share of cycling significantly reduces transportation emissions and traffic congestion as well. According to a case study in New Zealand (Lindsay et al., 2011), the results showed that by shifting only 5% of motor vehicle kilometers to cycling lead to a reduction of almost 223 million kilometers per each year, saving about 22 million liters of fuel and reducing 0.4% of greenhouse emissions.

Several studies have been carried out about multi-objective optimization problems involving safety concerns, traffic performance and emissions in urban areas for motor vehicle purposes (Wisemans et al., 2010; Chen and Zhang, 2013). However, there is a lack of research using multi-objective analysis in order to find the balanced solutions regarding traffic performance, safety and emissions in an integrated way for both of cyclists and motor vehicle drivers. For instance, Ehrgott et al. (2012) have applied a two criteria analyses for this purpose but this work considers three criteria with multiplying safety analysis which gives more complete work. Thus, the main objective of this paper is to optimize the choices of the routes that are carried out using the individual transport (motor vehicle) or the bicycle considering in this choice traffic performance, environmental and safety aspects. The final outcome of this work is ultimately to increase the use of more sustainable modes, namely the bicycle, by creating a methodology that can assist users and decision makers in their decision. This paper addressed the above concerns in a real-world urban network (with no of cycle paths) by evaluating the safety, traffic performance and global/local pollutant emissions.

This chapter is divided into four sections. Section one details background and objectives while section two establishes the methodology framework and methods. Then, section three explains the results and discussions. Finally, section four summarize the paper and concludes the findings and limitations.

4.2. Methodology

The methodology of this study was applied based on the real world case study in an urban road network in the city of Aveiro, Portugal. The present work uses a microscopic simulation platform of traffic (VISSIM) (PTV 2011) and emissions (Vehicle Specific Power – VSP) (Frey et al., 2002) to analyze traffic operations and to estimate carbon dioxide (CO_2) and nitrogen oxide (NOx) emissions generated by vehicles in the selected routes of the network. Furthermore, the Surrogate Safety Assessment Methodology (SSAM) (Gettman et al., 2008) was applied to assess road safety. Traffic movements were videotaped and second-by-second speed data and acceleration-deceleration rates were collected on-board a test-equipped vehicle and a bicycle. Subsequently, the collected data were coded in VISSIM after calibration and validation. The flowchart of methodology was illustrated in **Figure 4.1**.

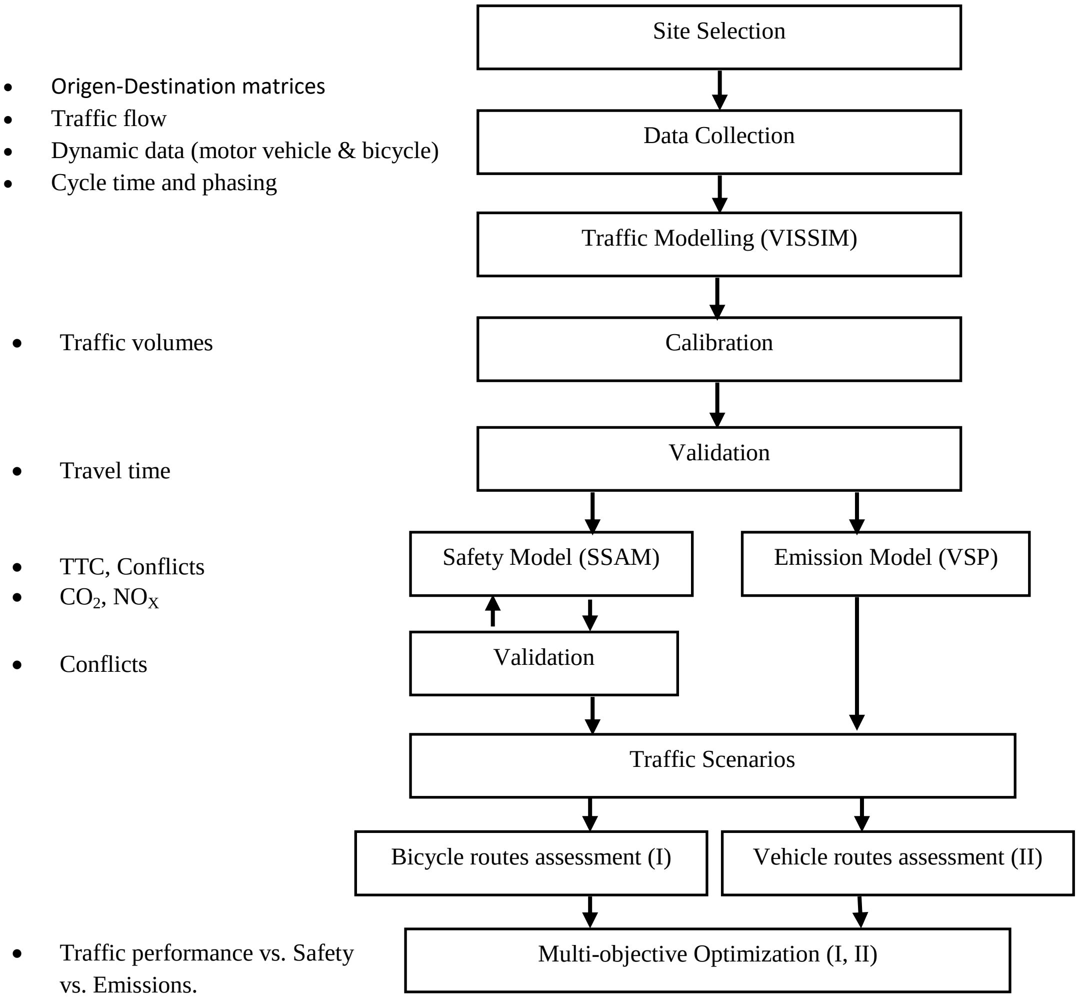

Figure 4.1. Methodological framework.

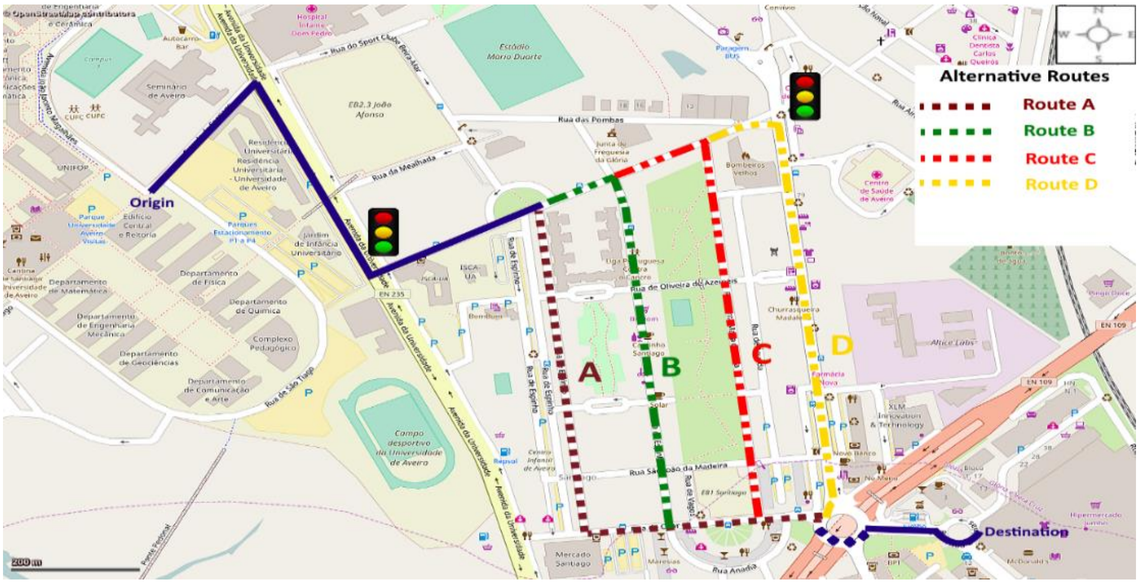

Figure 4.2. Layout of the case study.

4.2.1. Site selection and field data collection

Four alternative routes (A, B, C and D) between campus area of Aveiro University and a shopping center were evaluated according the methodology. Route A (Rua. Nova) with 6 m wide and 1.4 km distance, route B (Rua de Espinho) with 6 m wide and 1.6 km distance and route D with 8 m wide (in the end of the route the wide is changing to 6 m) and 2.1 km distance have two traffic flow direction while route C with 3 m wide and 1.7 km distance has only one traffic flow direction.

Traffic movements (included two three-leg intersections, one roundabout and four alternative routes, see **Figure 4.2**) was videotaped using four cameras and two manual traffic counters simultaneously. The cameras were placed near the intersections and roundabout. Data were collected in two days of a week, at morning and afternoon peak hours, from 9:30 a.m. to 11:30 a.m. and 5 p.m. to 7 p.m., respectively.

Also, Global Positioning System (GPS) collected second-by-second speed and acceleration-deceleration rates using a test-equipped vehicle and a bicycle as well.

A MATLAB code was developed to extract the study section data from the entire traveled data. The software automatically identified the first and last GPS points within the four alternative routes using the coordinates of the boundary study sections for each trip.

4.2.2. Traffic, safety and emissions modelling

VISSIM model was used to simulate traffic operations (PTV 2011). The capability of VISSIM in reproducing accurately traffic operations at microscale for both motor vehicles and bicycles in urban roads network is one of the main characteristics of this model (Twaddle et al., 2014). All simulation experiments were made for the analysis period of morning and afternoon peak hours with a 10-minutes “warm-up” period prior to load the study domain adequately with corresponding traffic flow.

Safety assessment traditionally relies on significantly crash data analysis. Based on this assessment the number of consequences of crashes have been used as measures of effectiveness to evaluate the safety performance of traffic facilities (Huang et al., 2013). SSAM automates traffic conflict analysis throughout processing motor vehicles and bicycles trajectories from a microscopic traffic model as is the case of VISSIM.

SSAM copies the trajectories of vehicles and bicycles from the traffic model and a record surrogate measure of safety. Then it determines whether such interaction can fulfill the condition to meet the conflict or not. The authors took the variable Time-to-Collision (TTC) as the safety indicator to assess whether a vehicle-vehicle and vehicle-bicycle interaction can lead to a conflict or not. A conflict is entitled whenever the TTC falls below the 1.5 s (Gettman et al., 2008) and TTC is a measure of conflict severity (low values of TTC indicate high severe conflicts).

The selected methodology to estimate the emissions is based on the concept of Vehicle Specific Power (VSP). This paper is focused on vehicular emissions of CO_2 and NOx. VSP is estimated from a second-by-second speed profile based on emission factors from typical Light-Duty Vehicles (LDVs) (Frey et al., 2002). Furthermore, VSP is associated with any speed trajectory and has capability to estimate the emissions at urban and even intercity roads (Bandeira et al., 2013). Eq. 1 provides the generic VSP equation from typical LDVs (Frey et al., 2002):

$$\text{VSP}= v.\,[1.1\text{ a} + 9.81\,(a.\tan(\sin(\text{grade}))) + 0.132] + 0.000302v^3 \quad (1)$$

where VSP is vehicle specific power (kW/metric ton); v is the instantaneous speed (m/s); a is the acceleration/deceleration rate (m/s^2); and grade is road grade (decimal fraction). Each VSP bin refers to one of 14 modes. Each VSP mode is defined by a range of VSP values which are associated to an emission rate. Each calculation of VSP results in a unique classification to a VSP mode (Coelho et al., 2009).

The following fleet composition has been used based on Portuguese car fleet distribution (ACAP 2014) was considered: 44.7% of light duty gasoline vehicles, 34.3% of light duty diesel vehicles and 21.0% of light commercial diesel vehicles. Other categories (transit buses and heavy duty trucks) represented only 1% of traffic composition and were excluded from the emissions calculations. Due to the flat terrain, the road grade was considered negligible.

4.2.3. Alternative routes assessment and Multi-objective optimization

In order to find the best route for cyclist and motor vehicle drivers for peak hours of the selected network, the traffic performance, emissions and safety-levels are simultaneously analyzed (**Figure 4.1**). The suggested alternative scenario is defined as: to examine the impact of route selection of case study on traffic performance, emissions and safety using motor vehicle or bicycle.

The Fast Non-Dominated Genetic Algorithm (NSGA-II) was applied in this study. This algorithm is one of the popular genetic evolutionary algorithms with high optimization quality ability for several multi-objective problem studies. Its particular fitness assignment scheme consists of sorting the population in different fronts using the non-domination order relation. Then, to form the next generation, the algorithm combines the current population and its offspring generated by the standard bimodal crossover and polynomial operators. Finally, the best individuals in terms of non-dominance and diversity are chosen (Moussouni et al., 2007). Moreover, NSGA-II was reported as one of the effective algorithm in finding a good approximation of an optimal Pareto front (Konak et al., 2006).

The following multi-objective tests were performed: 1) travel time-CO_2-1/TTC; 2) travel time-NO_X-1/TTC; 3) travel time-CO_2-number of conflicts; and 4) travel time-NO_X-number of conflicts. A set of 10 optimal solutions was considered for this analysis. The main objective is to create a three-dimensional multi-objective function to minimizing travel times, emissions and number of conflicts [or maximizing time-to-collision (minimizing 1/TTC)], simultaneously. Regarding the variable decision, the increment of network traffic volume was considered from 10% to 100% for both bicycles and motor vehicles. Regarding the traffic, emission and safety values of each optimal point, it would be possible to allocate a one or more routes for that point.

4.3. Results and discussions

4.3.1. Calibration and validation

The modified chi- squared statistics Geoffrey E. Havers (GEH), that incorporates both absolute and relative differences in comparison of estimated and observed volumes, was used as the calibration criteria for VISSIM (Buisson et al., 2014). In this case, 85% of the links must meet the GEH value lower than 4. In addition, the Mean Absolute Percent Error (MAPE) was used to measure the size of the error (deviation) for the observed and estimated traffic volumes.

Data collected from the selected intersection were used to calibrate and validate the simulation model (**Figure 4.1**). Calibration of VISSIM parameters was made based on estimated and observed traffic volumes with 15 random seed runs (Hale 1997). A good fit between observed and estimated data was obtained ($R^2 = 0.85$) using a linear regression analysis. Every link recorded a GEH value lower than 4 which satisfied the calibration criteria proposed by Dowling et al. (2004), while MAPE values were lower than 4%.

Regarding model validation, a comparison of observed and simulated travel time at the two main lanes before the main intersection of network, for North-South and South-North movements, was conducted using 100 floating car runs (Dowling et al., 2004). The difference between observed and estimated average travel time was not statistically significant at a 5% significance level. This demonstrated the accuracy of the traffic model in representing intersection-specific operations.

Regarding safety model validation, the 4 hours recorded videotapes of the main intersection of network (that is included in all alternative routes) were later reviewed for several times in order to obtain the traffic conflicts to record the information associated with each conflict (Huang et al., 2013), as shown in **Figure 4.3.** VISSIM model results were classified with 15-min time intervals. In order to be consistent with the conflict types used in SSAM, the observed conflicts were classified into three types: (a) Rear-end conflicts, (b) Lane-change conflicts, and (c) Crossing conflicts.

Linear regression analysis was conducted to identify if the simulated traffic conflicts provided reasonable estimates for the observed traffic conflicts. Linear regression models were fitted to relate the simulated conflicts to total observed conflicts in the site. It was found that the relationships between the simulated and the observed conflicts were statistically significant and acceptable (**Figure 4.3**).

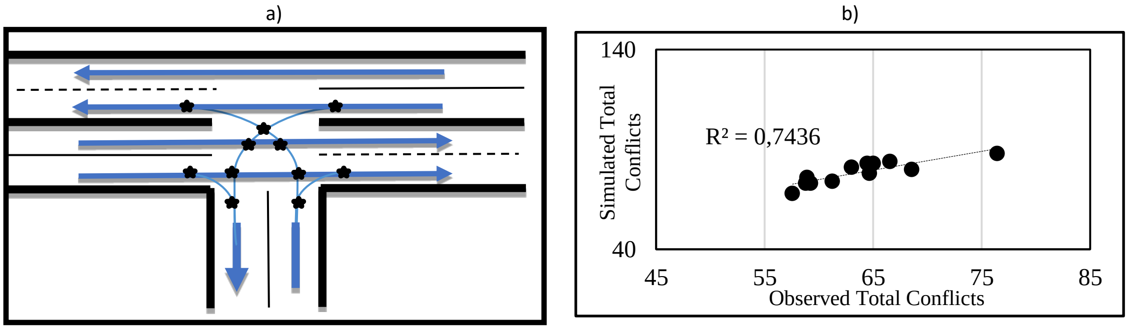

Figure 4.3. a) Conflict types observed at three-leg signalized intersection; b) Relationship between observed and simulated conflicts.

4.3.2. Results of alternative scenario

The summary of results regarding traffic performance, safety and emissions is represented in **Table 4.1** for both bicycle and motor vehicle drivers. The results showed that route A represents the shortest average travel time between origin and destination points for both bicycle with 461 s and motor vehicle drivers with 404 s.

Regarding safety concerns, since TTC variation is not significant between alternative routes (except route D that represents the worst option among others), the number of conflicts used to explain the safety level. Route C represents the safest route regarding number of conflicts compared routes A, B and D with 18.7%, 22.7% and 92% improvement respectively.

In terms of generated emissions by vehicles, route C represents the minimum rate for both CO_2 and NO_X while the average travel time for this route is more than A and B for both bicycle and motor vehicle users. This happens because the most part of this route has single direction and the traffic volume in this lane is less than others. Since route D includes two traffic lights (while others have only one traffic light) with highest traffic volume and longest travel time, the rate of emissions for both CO_2 and NO_X are more than others. If the cyclist or vehicle driver's criteria was defined in one dimension then the decision making would be easy to select the best route but if users have more than one criteria (section 2.3) then it is necessary to perform a multi-objective analysis since all there is trade-off between criteria.

Table 4.1. Summary results of alternative scenario I.

Route	Average travel time (s) (motor vehicle)	Average travel time (s) (bicycle)	Total conflicts (n)	TTC (s)	CO_2 (g/km)	NO_X (g/km)
A	**404**	**461**	89	1.14	192.6	0.370
B	455	497	92	1.14	193.6	0.340
C	510	638	**75**	1.13	**176.2**	**0.263**
D	656	774	144	1.08	246.9	0.456

4.3.3. Dedicated lane scenario

The dedicated lane for bicycle was created using VISSIM in previous case study. The summary of results regarding traffic performance, safety and emissions is represented in **Table 4.2** for both bicycles and MVs. The results showed that route A represents the shortest average travel time (as same a previous work) between origin and destination points for both bicycle with 379 s and MV drivers with 388 s. In general there is a reduction of travel time for MV in route A, B, C and D with 4%, 8%, 4% and 8% respectively and for bicycle with 18%, 6%, 11% and 13% respectively.

It was surprised that some of the travel times of bicycle using dedicated lane is shorter than vehicles travel time without the proposed dedicated lane. For example, bicycle is faster in route A and B with travel time 379 s and 468 s respectively, than MVs with speed 404 s and 455 s respectively. Regarding safety concerns, since TTC values increased for all the routes except route D. It showed that time-to-collision is improved because higher TTC values mean less severe conflicts. The number of conflicts also decreased for routes A, B, C and D with 24%, 13%, 19% and 15% respectively. However, route C represents the safest route among others regarding number of conflicts and TTC value. In terms of generated emissions by vehicles, route C represents the minimum rate for both CO_2 and NO_X while there is no significant improvement for NOx emissions. The maximum improvement of NO_X emissions was 3% when the network operate with and without bicycle facility but about CO_2 emissions the results showed 6%, 2%, 6% and 7% for routes A, B, C and D respectively. It should be mentioned that route D has the highest rate of emissions regardless the proposed dedicated lane since includes two traffic lights (while others have only one) with highest traffic volume and distance between origin and destination. In general results approved that there is an improvement regarding traffic performance, safety concerns and emissions for both bicycle and MV drivers when the bicycle lane is separated from traffic lanes of network.

Table 4.2. Summary results of previous work and dedicated lane scenario.

Route		A	B	C	D
Average travel time (s) (motor vehicle)	Without bicycle lane	**404**	455	510	656
	With bicycle lane	**388**	419	490	603
	Increase/decrease	-4%	-8%	-4%	-8%
Average travel time (s) (bicycle)	Without bicycle lane	**461**	497	638	774
	With bicycle lane	**379**	468	570	671
	Increase/decrease	-18%	-6%	-11%	-13%
Total conflicts (n)	Without bicycle lane	89	92	**75**	144
	With bicycle lane	68	80	**61**	123
	Increase/decrease	-24%	-13%	-19%	-15%
TTC (s)	Without bicycle lane	1.14	1.14	1.13	1.08
	With bicycle lane	1.20	1.23	**1.23**	1.0
	Increase/decrease	+5%	+8%	+9%	-7%
CO_2 (g/km)	Without bicycle lane	192.6	193.6	**176.2**	246.9
	With bicycle lane	181.4	190.1	**165.6**	228.2
	Increase/decrease	-6%	-2%	-6%	-7%
NO_X (g/km)	Without bicycle lane	0.370	0.340	**0.263**	0.456
	With bicycle lane	0.358	0.331	**0.260**	0.444
	Increase/decrease	-3%	-3%	-1%	-3%

4.3.4. Multi-objective analysis

The previous findings (**Table 4.1**) give some useful information for passengers (bicycle and motor vehicle users) and decision makers to assess each alternative routes based on one or two dimensions. For instance, route A is the best regarding travel time for both bicycle and motor vehicle users and route C is the best regarding emissions and safety concerns. However, multi-objective analysis should be considered in order to find the balanced solutions regarding traffic performance, safety and emissions in an integrated way for both bicycle and motor vehicle users. The main objective of this section is to minimize the travel time, emissions and number of conflicts for actual traffic demand of vehicles and bicycles which are included in the network.

Figure 4.4 presents the main results of the alternative scenario as a result of multi-objective optimization of the average travel time (traffic performance), CO_2 and NOx (emissions per unit distance) and the number of conflicts (safety). The analysis of the convergence to Pareto fronts and the diversity of solutions indicated that a maximum of 150 iterations were sufficient to reach convergence. With reference to crossover and mutation, each solution of the final Pareto fronts not differed much by using different rates of those measures. Therefore, the crossover rate was set at 95%, and the mutation rate was set at 10%. The resulted solutions from scenarios are illustrated in **Figure 4.4** which illustrates the Pareto fronts estimated from the initial (1st iteration) to final (150th) populations. For each scenario three dimensions were defined; travel time (x-axis), CO_2 and NO_X (y-axis) and conflicts (z-axis). Each point based on its coordinate (values of time, conflicts and emissions) belongs to one or more alternative routes.

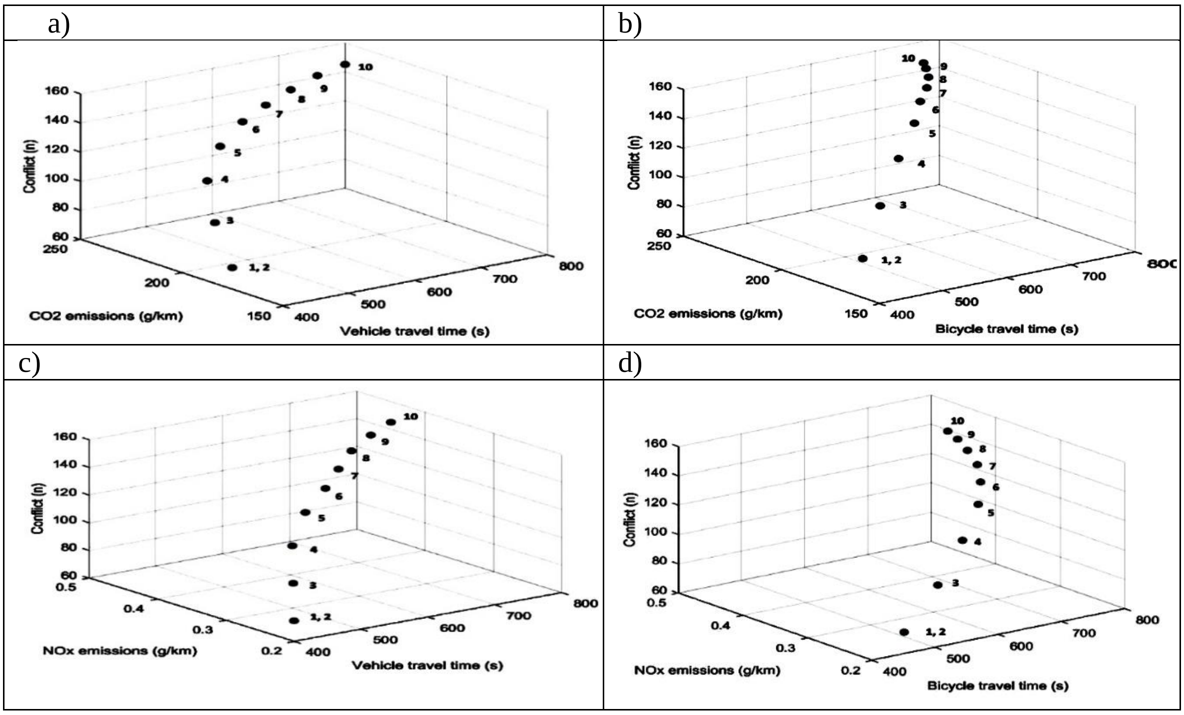

Figure 4.4. The approximate final Pareto front: a) Travel time, CO_2 and Conflicts for motor vehicle users; b) Travel time, CO_2 and Conflicts for bicycle users; c) Travel time and NO_X, Conflicts for motor vehicle users; and d) Travel time, NO_X and Conflicts for bicycle users.

For instance, adopting a solution number 6, from **Figure 4.4** (a), the values of travel time (s), CO_2 (g/km) and number of conflicts (n) are 651, 243 and 123, respectively. The values show that routes A, B and C can be allocated for this point. Also, adopting a solution number 6, from **Figure 4.4** (d), the values of travel time (s), NOx (g/km) and number of conflicts (n) are 705, 0.32 and 117, respectively. The values show that routes B and C can be allocated for this point. Regarding more repetition of route C compared to the other routes it can be concluded that it can be the best option for bicycle and motor vehicle users as a result of multi-objective analysis.

4.3.5. PC-Crash simulation for motor vehicle and bicycle collision

PC-crash is a well-known software that widely used in crash reproductions based on dynamics characteristics among all the reproduced software (Yuan et al., 2002). The main objective of this section it to explore the relationship between the MV speed and the cyclist injuries. Head impact point is considered as the main factor to analyze the injuries impact. In this way the distances from the cyclist head impact location on the vehicle to the front of the vehicle (CHID) was defined to represent head impact point (Yuan et al., 2002).

In this way, collision speed and angle of collision point is important to analyze. Concerning motor vehicle-bicycle collision some factors such as collision angle, collision speed, vehicle shape and initial position are important because can highly affect the safety results (Yuan et al., 2002, Lin et al., 2010). In general Initial position, impact direction, vehicle shape and collision velocity are the main factors that influence the cyclist kinematics.

PC-Crash (version 11.1) performed a rear-end collision accident scenario of MV-bicycle in normal weather and road conditions. Based on SSAM manual definition if conflicts angle is $\leq 30°$ the rear-end conflict occurred between two vehicles (Gettman et al., 2008). In this study the collision angle assumed 30° between bicycle and MV. The variation of actual vehicle speeds that was used for traffic model validation (from up to down) was included in PC-Crash in order to explore the impact velocity from optimizer tool of software (**Table 4.3**). The variation of initial speed for MVs was between 32 km/h (min) and 88 km/h (maximum).

The sequence of collision was considered as follows: reaction-deceleration-start-deceleration. The general parameters of MV (length, width, height, wheelbase, front overhang and track and etc.), driver (female, 65kg), bicycle (28 kg) and cyclist (Female, 65 kg and a height of 1.75m) were included in the model. Furthermore, impact parameters such as coefficients of restitution (0.1) and friction (1.0) were included to model as recommended by PC-Crash (version 11.1).

The average of bicycle speed was set to be 5 km/h (as a result of previous work in selected lanes for model validation) and considered as a constant speed. The longitudinal distance between bicycle and MV is assumed 3.5 m before starting the collision simulation with 30° angle. Regarding car model building in PC-Crash one of the common used vehicles in Portugal (Renualt Clio, model 2015) was selected from vehicle database. Since the shape of MV can influence the impacts results for this model we used the most common light car model. Regarding bicycle model building one bicycle with multi-body (the body of cyclists is divided in 16 parts) characteristics was selected as bicycle model in the database of vehicle model (**Figure 4.5**).

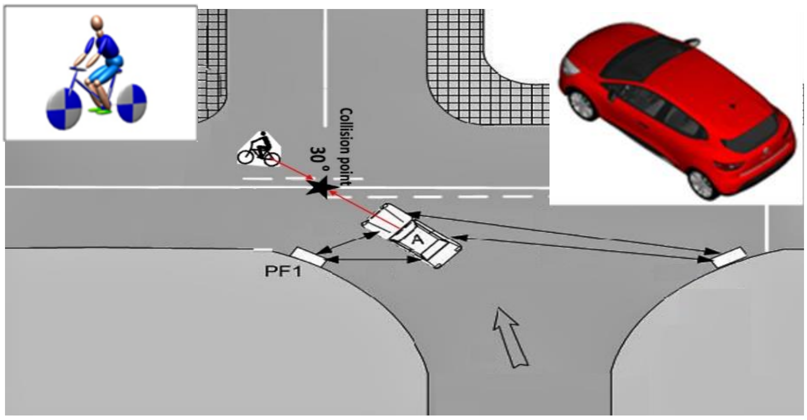

Figure 4.5. Collision type (rear-end 30°) for selected MV and bicycle.

The results of simulation showed that the longitude cyclist head impact location on the vehicle to the front of the vehicle when the velocity impact is less than 45 km/h and more than 60 km/h (maximum 81 km/h) is longer than when velocity impact is between 45 km/h and 60 km/h. As illustrated in **Figure 4.4** from PC-Crash, the cyclist head impact location in the maximum velocity impact is in the middle of the windshield.

Table 4.3. Longitudinal distance of cyclist head impact point with 30° collision angle.

Number of simulation run	MV impact velocities (km/h)	CHID (m)
1	**38.5**	**1.6**
2	**42.6**	**1.4**
3	**45.0**	**1.4**
4	**48.8**	**1.2**
5	**52.2**	**1.0**
6	**55.1**	**1.0**
7	**58.5**	**1.1**
8	**60.0**	**1.4**
9	**64.3**	**1.5**
10	**66.4**	**1.5**
11	**69.3**	**1.6**
12	**70.5**	**1.8**
13	**75.2**	**1.9**
14	**78.6**	**1.9**
15	**81.0**	**2.0**

4.4. Conclusions

This research proposed a multi-objective scenario for bicycle and motor vehicle route optimization in order to improve traffic performance, emissions and safety. The analysis was based on a microscopic approach using VISSIM traffic model together with VSP methodology and SSAM model. Average travel time, CO_2 and NOx vehicular emissions and number of conflicts were the outputs analyzed in this paper. As a solution algorithm for the models the Fast Non-Dominated Genetic Algorithm (NSGA-II) was used to search the optimal solutions for the suggested alternatives. The results classified the selected alternative routes based on the each traffic performance, safety level and emissions rate separately and these results can be useful for users to choose the optimum route based on individual preferences. In this way, route D represents the worst performance regarding travel time, conflicts and emissions. Route C requires more travel time than route A (fastest alternative) for motor vehicle and bicycle users, with 106 s and 177 s respectively, but represents the best performance regarding safety and emissions. Furthermore, each point of optimum solutions from Pareto front based on its travel time, safety and emissions value can be defined in one or more selected routes. The results of multi-objective analysis represent route C as the best option for both bicycle and motor vehicle users.

Sensitivity analysis of road users' criteria for each specific transportation network can be useful for urban network designers and planners in order to improve traffic performance besides the environmental and safety concerns. Since this study was focused on the role of bicycle and vehicle in route selection, further studies about different transportation mode such as walking and more limitations such as cost, weather conditions can be useful for network designers and planners.

Regarding the results of dedicated lane for bicycle, in general the results showed that presence of dedicated lane can improve traffic performance, safety and emissions for both cyclists and MVs.

In this way, route D represents the worst performance regarding travel time, conflicts and emissions. Route C represents the best performance regarding safety concerns and rate of emissions while route A represents the best performance regarding travel time with 404 s and 388 s for MV and bicycle respectively. Furthermore, route A and B represent less travel time for bicycle than MV. Since this study carried out based on the role of bicycle and MV in route selection, further studies are needed considering the role of pedestrians, adverse weather conditions in different urban areas.

Regarding the results of PC-crash, it was found that collision angle, collision speed and vehicle shape can highly affect the safety results. Moreover, the cyclist head impact location in the maximum velocity impact (81km/h) is in the middle of the windshield. The same simulation of PC-Crash can be performed for MV-bicycle using different type of accident with different degree of accident point. The speed of bicycle was considered constant in this study. Since different speeds of bicycle can lead to different safety results it is suggested to consider in future work. It is important to mention that front shape of selected MV can highly change the results of simulation. In this way it is recommended to repeat the same analysis using different type of MVs.

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5. INTERACTION BETWEEN MOTOR VEHICLES AND BICYCLES AT TWO-LANE ROUNDABOUTS: A DRIVING VOLATILITY BASED ANALYSIS

Drivers' instantaneous decisions regarding speed and acceleration/deceleration, as well as the time rate of acceleration change (jerk) can result in a volatility driving behaviour with significant impact on cyclist safety.

The contribution of this research is the assessment of driving volatility in MV-bicycle interactions at two-lane roundabouts. Traffic flow and bicycle GPS data were collected from two two-lane roundabouts. Then, traffic, emissions and safety models were used to evaluate volatility impacts on safety, pollutant emissions and traffic performance.

The findings showed jerk have impact on driving volatility between MVs and bicycles, regardless of roundabout design with a higher amplitude of variation for MVs. However, MVs had higher acceleration-deceleration variation than bicycles.

5.1. Introduction and objectives

Policy revisions, infrastructure improvements, and individual benefits of bicycles along with positive effects on air pollutants and environmental issues have led to the increase of cycling rate at urban areas (Twaddle et al., 2014; Silvano et al., 2015). The impact of modal shift from to car to cycling and public transportation can result in relevant health benefits, especially those regarding the increase of physical activity, and secondary in the reduction of air pollution impacts (e.g. particulate matter < 2.5μm) in population (Rojas-Rueda et al., 2012). According to the European Cyclists' Federation (EFC), the economic benefits of cycling regarding carbon dioxide (CO_2) emissions, air pollution and noise were estimated by 3bn € in the 28 European-countries (EU28) (Ferguson et al., 2018).

One concern that arises from bicycle use is the risk-exposure for cyclists (Fernandez-Heredia et al., 2014). In 2016, about 2,000 cyclists were killed in road traffic accidents in EU28, constituting 8% of all road accident fatalities. In 2016, 51 cyclists died after crashing at roundabouts in EU28 (approximately 2.5% of the cyclist-intersection fatalities) (EC 2018).

The benefits of roundabouts are well-reported: lower number of conflict points than the traditional stop-controlled and signalized intersections, low approaching and circulating speeds, and effectiveness in reducing unnecessary driving volatility by reduction in motor vehicle (MV) stops (Rodegerdts et al., 2007; 2010; Jensen, 2017). Nevertheless, cyclists at roundabouts constitute a specific problem for safety at roundabouts (Rodegerdts et al., 2010; Brilon, 2016; Ferguson at al., 2018).

The bicycle facility and infrastructures (Koorey and Parsons, 2016; Daniels et al., 2009), speed limits (Silvano et al., 2015), design (Jensen 2017), and traffic volumes (Rodegerdts et al., 2010) are pointed out as factors that can influence bicycle safety at roundabouts. Speed is a fundamental risk factor in cyclist safety (Silvano et al., 2015), especially at roundabout entry and exit legs while the MV and bicycle are circulating near each other. Speed also plays an important role in the definition of driving style based on the speed limits and driver's decision in choosing the proper speed (Liu et al., 2017). The prior research showed a positive correlation between the frequency of driving speed exceeding the speed limit and the number of road traffic crashes (af Wåhlberg 2006). Moreover, it can result in the increasing volatility driving behaviour of MV driver during MV-bicycle interaction. In this situation, drivers might have to rapidly adapt by changing speed, acceleration/deceleration variation or vehicular jerking (which is defined by the change in the rate of acceleration or deceleration) to avoid the collision. The instantaneous yielding behaviours of drivers and cyclists, such as rapidly braking or acceleration can dictate safety concerns.

Drivers' instantaneous decisions to change speed and subsequently acceleration/deceleration (aggressive driving behaviours) affect energy consumption significantly, emissions, and safety outcomes (Liu et al., 2017; Wang et al., 2015; Park et al., 2009). According to a recent study by Liu et al., (2017), volatility driving is associated with speed and acceleration variation or vehicular jerking by drivers, which in turn increases the fuel consumption and risks of crash occurrence. Vehicular jerk is a change rate of vehicle acceleration with respect to time as a result of aggressive driving, fast shifting gears, and hard braking. Mathematically, jerk is defined as the first derivate of acceleration/deceleration (second derivate of speed) with positive or negative value.

Sudden or rapid variation in speed and subsequently in acceleration/deceleration means changing driving behaviour in a very short period that is not enough to driver and other road users react properly (Feng et al., 2017). Speed variation and subsequently acceleration/deceleration variation are the main factors of driving volatility for both bicycle and MV. Wang et al. (2018) showed that a high volume of speed variation was associated with increased crash frequency. However, the correlation between volatility driving and crash risk has been found in previous studies (Zaki et al., 2014; Feng et al., 2017).

Kamrani et al., (2018a) introduced a new way to measure the vehicle volatility for alternative fuel vehicles, based on time-varying stochastic volatility. The research was not only based on driver styles (vehicular speed, acceleration, jerk) but also different types of vehicles (hybrid, plug-in, hybrid electric, CNG, and electric vehicles). The findings showed that these vehicles are less volatile compared to conventional vehicles.

The cyclist impedance effect increases under high bicycle volumes thereby affecting intersection-specific capacity and increasing vehicular emissions. Research around this topic is widespread [about safety: (Jensen 2017; Brilon 2016; Daniels et al., 2008; 2009), about safety-traffic performance (Rodegerdts et al., 2007; Silvano et al., 2015), and about safety-emissions-traffic performance (Roach 2015)], but little was discussed about MV-bicycle interaction at roundabouts or driving volatility. The few studies around this topic analysed the impacts of driver biometrics data (Kamrani et al., 2018b), infrastructure (Kamrani et al., 2018b) and alternative fuel vehicles (Kamrani et al., 2018a) on driving volatility. This happens not only for MVs but also between MVs and bicycles. Several studies have been focused on the impact of the roundabout on cyclist safety (Rodegerdts et al., 2010; Jensen 2017; Koorey and Parsons, 2016; Daniels et al., 2008; 2009), but they did not include the effect of driving volatility and the role of MV-bicycle interaction.

Thus, the motivation of this research is to assess the impact of driving volatility of cyclists and MVs on traffic performance, vehicular emissions, and cyclist safety. Speeds and acceleration variation (jerk) were analysed in the circulating area of the roundabout to assess the influence on: 1) drivers' volatility interacting with cyclists; 2) emissions and 3) corresponding roundabout-specific traffic performance and safety outcomes. This research investigates these concerns at real-world two-lane roundabouts without dedicated bicycle lanes in urban areas that experience different designs, and traffic and bicycle demand. The novelty of this research is assessment of the impacts of cyclists and MVs driving volatility [not only MV like in previous research (Kamrani et al., 2018a, Liu et al., 2017; Wang et al., 2015)] on traffic performance, safety and emissions at roundabouts on an integrated way. The specific objectives of this paper is threefold:

- To identify the main factors of driving volatility as a result of MV-bicycle interactions at two-lane roundabouts;
- To investigate the impact of driving volatility on CO_2, carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxides (NO_X) emissions per unit distance;
- To evaluate the impact of MV-bicycle interaction on traffic performance and cyclist safety.

5.2. Methodology

The main idea of the methodology was to combine field measurements and microsimulation tools to characterize MVs and cyclists iterations at two-lane roundabouts. First, data were collected from studied locations, then the jerk, acceleration and speed were analysed for MVs and bicycles. Along these, the Vehicle Specific Power (VSP) methodology were used to estimate CO_2, NO_X, CO, and HC emissions generated by MVs. In turn, simulation uses a microscopic traffic model paired with safety model (Surrogate Safety Assessment Model – SSAM) to examine MV-bicycle interactions at roundabouts and to estimate conflicts resulting from MV-to-MV and MV-to-bicycle interactions and the following safety indicators: Time-to-Collision (TTC), Post-Encroachment Time (PET), Deceleration Rate (DR), maximum speed (MaxS) and maximum relative speed difference (DeltaS) (Gettman et al., 2008). **Figure 5. 1** illustrates the conceptual framework of the research.

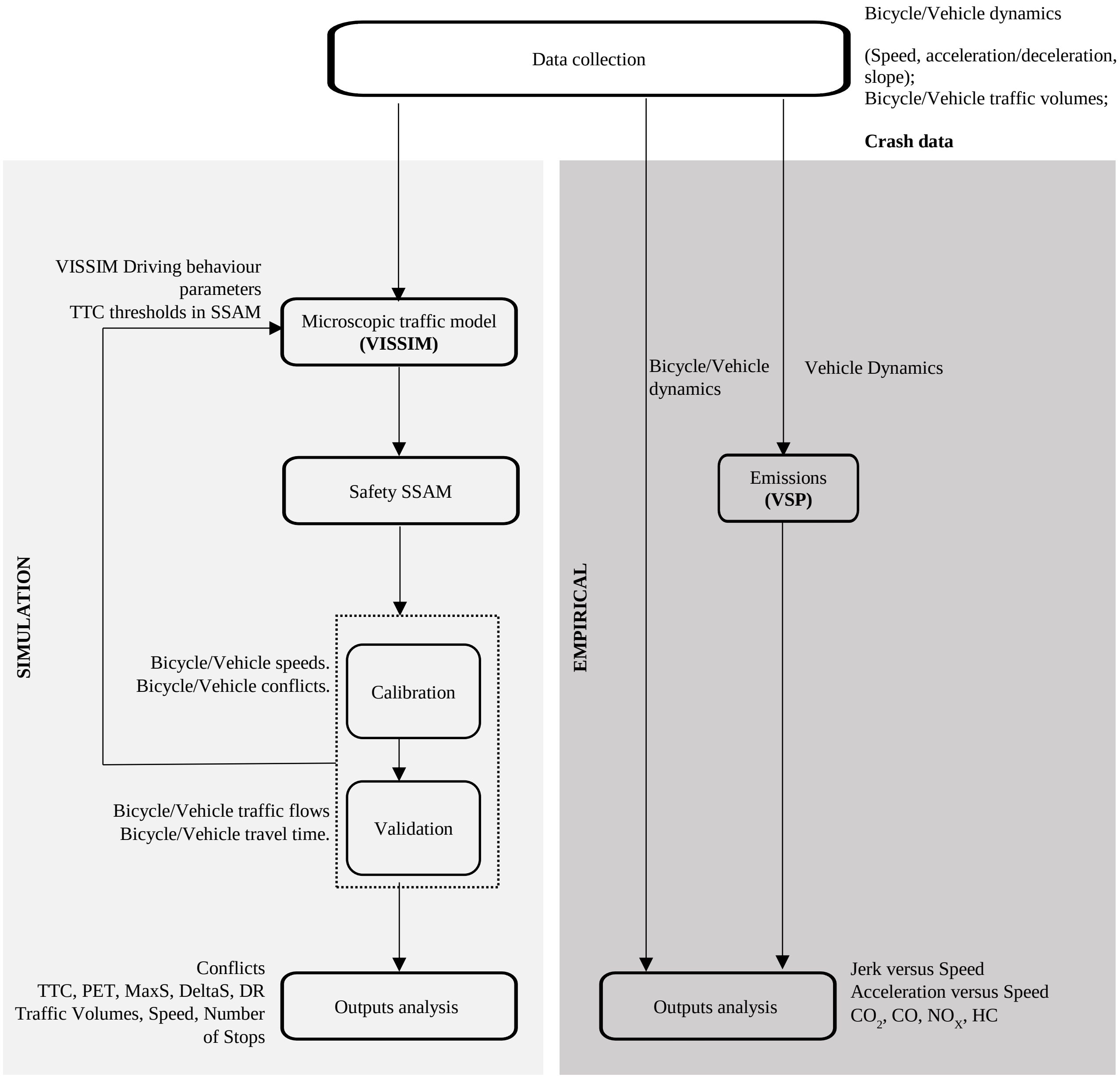


Figure 5.1. Methodological framework.

5.2.1. Traffic modeling and emission estimates

VISSIM (PTV 2016) offers good support for modelling driving behaviour parameters (e.g., gap acceptance and lateral movements) in roundabouts (Li et al., 2013) and it is also able of reproducing the complex nature of interactions between vehicles and bicycles at roundabouts (Bergman et al., 2011; Abhigna et al., 2016). The study of bicycle movements and behaviour parameters are highly important for bicycle simulation and calibration procedure (Ma and Luo, 2016) and for calibration process as well.

Emission estimation is based on the concept of Vehicle Specific Power. The scope of analysis is focused on vehicular emissions for global (CO_2) and local (NO_X, CO, and HC) pollutants. VSP is computed from a second-by-second speed profile based on parameter values for a typical Light-Duty Vehicle (LDV) (Frey et al., 2002). VSP is associated with any speed trajectory and it provides reliable vehicular emission estimates at roundabouts since it accounts for changes in vehicle dynamic in the approach, circulating and exit areas (Coelho et al., 2006; Salamati et al., 2013). Equation 1 provides the generic VSP equation from a typical LDV (Frey et al., 2002):

$$VSP = v\,.\,[1.1\,a + 9.81\,(a\tan(\sin(grade))) + 0.132] + 0.000302v^3 \tag{1}$$

Where: VSP – vehicle specific power (kW/metric ton); v – Instantaneous speed on a second-by-second basis (m/s); a – acceleration-deceleration rate on a second-by-second basis (m/s^2); grade – road grade (%).

Each VSP bin refers to one of 14 modes. Each mode is defined by a range of VSP values that are associated with an emission factor for CO_2, CO, NO_X and HC concerning the Gasoline Passenger Vehicles (GPV) (Anya et al., 2013), Diesel Passenger Vehicles (DPV) and Light Duty Diesel Trucks (LDDT) (Coelho et al.2009).

5.2.2. *Safety* model

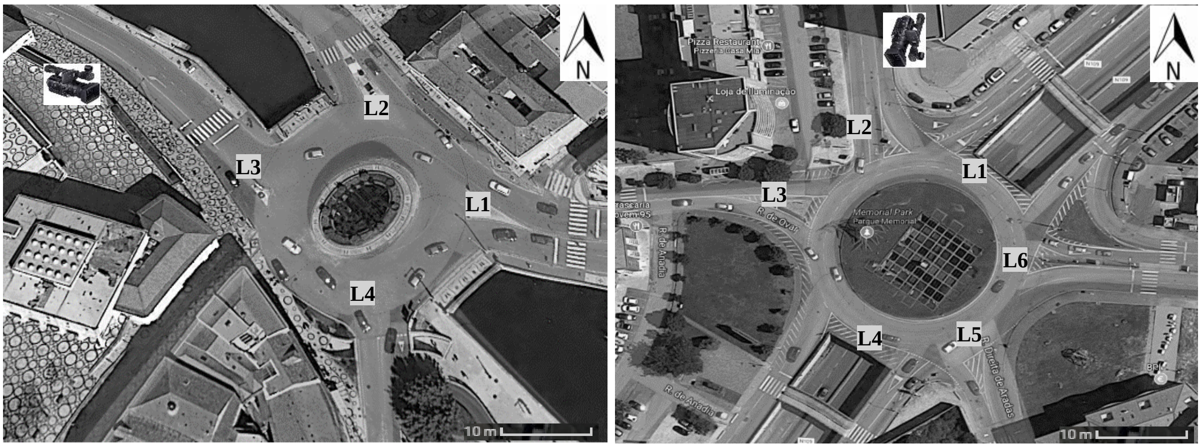
SSAM (Gettman et al., 2008) was selected to simulate traffic conflicts between MVs, and between MV and bicycles. This post-processing tool automates traffic conflict analysis using vehicle and bicycle trajectories from a microscopic traffic model as VISSIM. Afterwards, it records surrogate measures of road safety and determines whether an interaction between MV-to-MV and MV-to-bicycle satisfies the condition to be considered a conflict (Gettman et al., 2008).

A good body of research have identified some limitations of SSAM tool, namely: i) inability of evaluating complex real-world driving behaviors, for instance interactions that results in side-wipe conflicts; ii) it only provides a graphical user interface which became automatic calibration procedure impracticable (time consuming); and iii) unviability of SSAM to determine the probability of each estimated conflict turning into a crash (Gettman et al., 2008; Huang et al., 2013; Fernandes et al., 2019).

TTC is used as a threshold to define whether a MV-MV and MV-bicycle interaction is a conflict. This surrogate measure is defined as the minimum time-to-collision of two MV or MV-bicycle on a collision route. Minimum TTC and PET are used to assess the severity of a given conflict event while DR, MaxS and DeltaS are indicators of the potential crash severity (Gettman et al., 2008).

5.2.3. Site selection and studied locations

To evaluate the impacts of driving volatility between cyclists and MVs on traffic performance, emissions, and cyclist safety, two conventional two-lane roundabouts in the urban area of Aveiro (Portugal) were selected. Roundabout R1 is in the city centre with an average of 65 bicycles per hour (bph) (**Figure 5.2 a**). There are positive slopes up to 3.5% between some roundabout legs and central island that creates some visibility problems for both approaching vehicles and cyclists. Roundabout R2 is an interchange roundabout with six legs. The number of cyclists is 12 bph (**Figure 5.2 b**).


a) Roundabout R1

b) Roundabout R2

Figure 5.2. Layout of the case studies with the identification of legs and videotaping location. [Source: Google Maps]

The R1 and R2 were chosen due to the fact that they have the same number of circulating lanes and absence of dedicated bicycle lanes, but variations in bicycle demands, design, and capacity.

Crash data involving motor vehicles and cyclists at R1 and R2 were gathered for 3-years' time period between 2015 and 2017 (ANSR 2019). The database covered a total of 11 and 2 crash observations at R1 and R2, respectively, and with the following distribution of mode of transportation: R1 – 7 two-vehicle crashes (motor only); R1 – 4 crashes involving a motor vehicle and a cyclist; R2 – one single-vehicle crash; R2 – one crash involving a motor vehicle and a pedestrian.

The cameras were set up in the field to adequately cover the entire roundabout movements. This data collection was carried out for both morning and afternoon peak periods (8-10 AM and 5-7 PM), under dry weather conditions, for two days. Complementary, GPS data can help to capture drivers' volatility behaviours (Wang et al., 2015) interacting with bicycles. Thus, a test-equipped MV and a bicycle with GPS collected second-by-second speed, distance travelled, and acceleration-deceleration rates. Total data included more than 6 000 seconds of vehicle and bicycle GPS data. In order to assure variability in field tests, three different test-drivers (two male and one female) and two different test-cyclists participated in both vehicle and bicycle GPS data collection, respectively. The details of MV-bicycle interactions were recorded by co-pilot on the provided data sheets during test periods. Time, location and type of interaction defined by Sakshaug et al. (2010) were recorded during GPS data collection. The locations of interactions were categorized as entry lane, exit lane, parallel movement, and circulating. Vehicular jerk values were collected as the second derivative of speed (the derivative of acceleration) based on the provided data from GPS. Other variables, such as enter and exit traffic volumes, queue lengths and conflicting traffic flow were extracted from video data. The Level-Of-Service criteria (LOS) and queue distance by lane were collected from traffic data measurements using the Highway Capacity Manual methodology (TRB 2016). The key characteristics of case studies are summarized in **Table 5.1.**

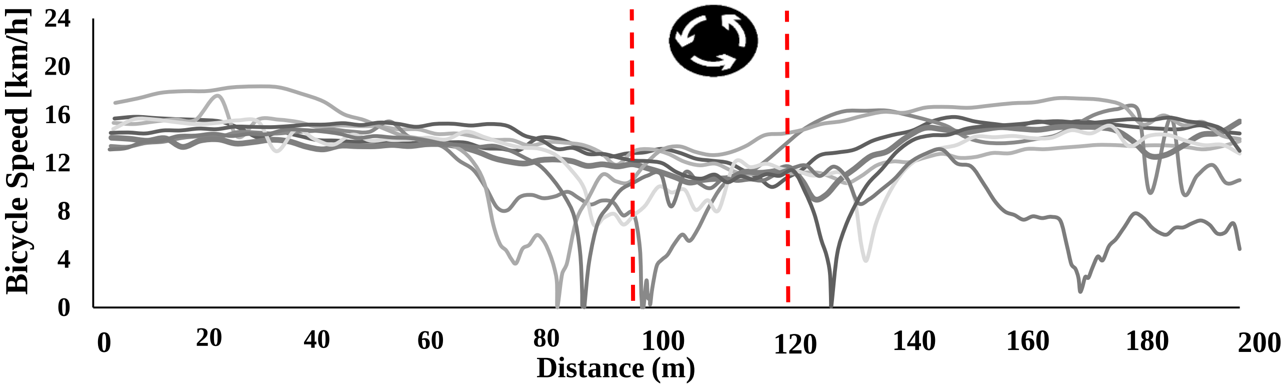
Table 5.1. Key characteristics of candidate case studies during the field measurements periods

Roundabout	Circulating Width [m]	Central Island [m]	Leg	LOS	Queue [m]	Entry traffic [vph]	Exit traffic [vph]	Entry bicycles [bph]	Exit bicycles [bph]	Intersection LOS
R1 (Aveiro city center)	8	22/18[a]	L1	C	98	526	382	26	29	C
			L2	C	48	232	159	18	14	
			L3	D	114	550	475	22	25	
			L4	B	41	327	433	20	11	
R2 (Shopping center)	8	40	L1	F	135	381	756	3	0	D
			L2	C	86	581	492	10	10	
			L3	D	80	278	410	9	7	
			L4	C	205	628	268	2	0	
			L5	D	118	442	373	4	9	
			L6	B	73	677	537	11	16	

[a] *Oval roundabout which has two values for Central Island*

Figure 5.3 a-b shows all combinations of bicycle speed profiles with none, one and multiple stops that were extracted from GPS data at R1 (L3 →L1) and R2 (L6 →L2). For this analysis, an average roundabout influence area of 200 m was considered in the simulation. This is defined as the sum of the deceleration distance that a vehicle travels from cruise speed as it approaches the roundabout and enters the circulating lane and acceleration distance as it leaves the roundabout up to the point it regains the cruise speed (Fernandes et al., 2016). In certain occasions due to the pedestrian crossing (Bergman et al., 2011) and congested traffic at R1 and R2, cyclists stops before and after circulatory carriage. In summary, cyclist speed profiles followed the same pattern as MV did (Salamati et al., 2013) with deceleration from upstream to circulating area of roundabout followed by an acceleration while the cyclist is leaving the roundabout.

a)



b)

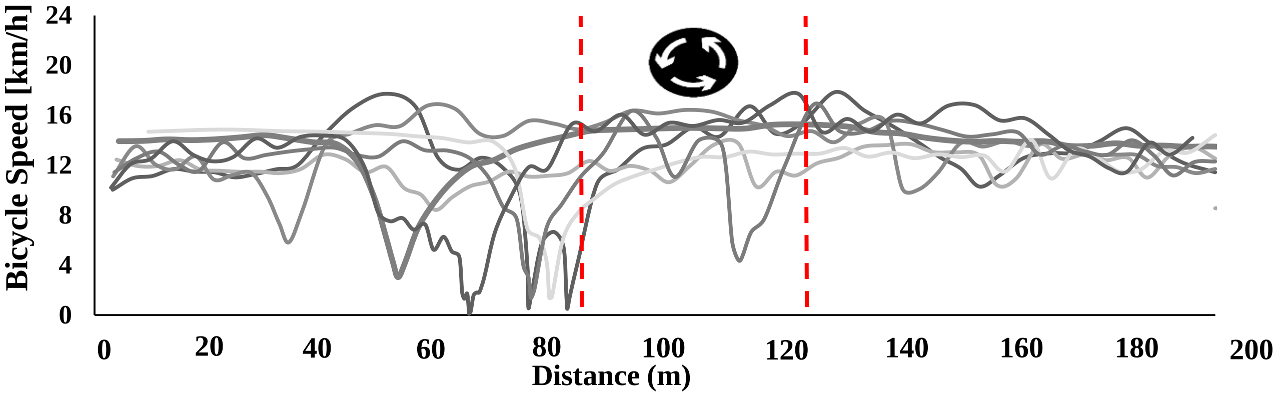


Figure 5.3. Representative speed profiles for a bicycle: a) R1 (L3 →L1) and b) R2 (L6 →L2).

5.2.4. Traffic Model Coding, and Calibration and Validation procedures

The simulation was separately done for each roundabout between 6:20 PM and 7:30 PM. A “warm-up” was included during the first 10-minutes to load the road network with corresponding flows. The treatment of the yield areas took into account local-specific headway and critical gaps. Regarding MVs and bicycles movement in the shared road without any physical barrier, some parameters, such as overtaking opportunities and lateral lane position for both cyclists and drivers were considered (besides speed distribution, road width, and number of lanes or volumes).

VISSIM traffic model was initially calibrated to reproduce traffic and bicycle flows R1 and R2 by coded link. Thus, a sensitivity analysis of VISSIM driving behaviour parameters (car-following, gap-acceptance, and lane change) was carried out to assess their impacts on traffic and bicycle volumes (Fernandes et al., 2016). This comparison was done using 10 different runs (Hale 1997). The modified chi-squared statistics Geoffrey E. Havers (GEH), which incorporates both absolute and relative differences in the comparison of estimated and observed volumes, was used as the calibration criteria (Dowling, Skabardonis, & Alexiadis, 2004). In this research, the model calibration compared MV and bicycle flows and travel time between estimated and observed data. The calibration criterion was that GEH should be less than 4 at least 85% of the coded links (Dowling et al., 2004).

SSAM was also calibrated by comparing estimated and observed conflicts between MVs and bicycles. Using videotaping, the research team obtained the traffic conflicts (Huang et al. 2013) in both R1 and R2 in 15-min intervals. To be consistent with the conflict types computed by SSAM, the observed conflicts were classified into three types: a) Rear-end conflicts; b) Lane-change conflicts: and c) Crossing conflicts. After that, SSAM conflicts for both sites were computed for a TTC range interval from 1.0 to 2.0 seconds with 0.1-increment. TTC = 1.5 was adopted for urban areas to define a conflict, as suggested by Huang et al. (2013). Then the obtained number of MVs-bicycle conflicts were compared against observed data for each TTC value to find the optimum TTC value for each study case.

There are virtual crashes, i.e. conflicts with TTC = 0 seconds that are reported by SSAM. These phenomenon result from abrupt lane-change behavior while vehicles are entering, circulating or leaving roundabouts or failing to yield to conflicting traffic at low gaps. Therefore, the research team filtered out TTC equal 0 after calibration, either by correcting coded links or at adjusting driving behavior parameters, until virtual crashes represented less than 10% of total conflicts (Fernandes et al., 2019).

Model validation compared observed and simulated bicycle and MV speeds by coded link using the optimal VISSIM calibrated parameters with 10 random seed runs.

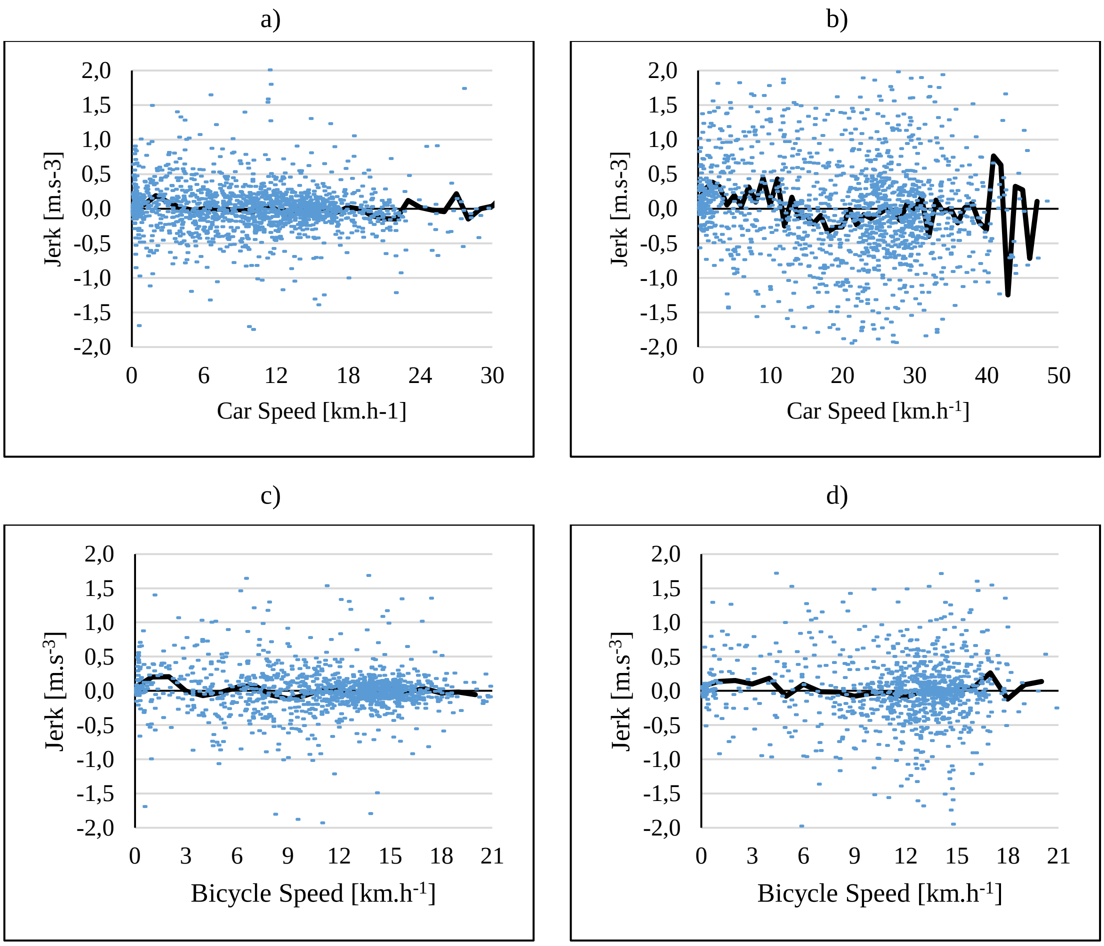
5.3. Results

In this section, the main results from the field measurements are analysed (Section 3.1) followed by the simulation calibration and validation (Section 3.2) and safety analysis (Section 3.3).

5.3.1. Field Measurements

5.3.1.1. Jerk versus Speed

Jerk values were plotted against speed for both motor vehicles and bicycles, as depicted in **Figure 5.4 a-d.** Each value of jerk represents the difference between acceleration is the second of travel i+1 and acceleration is the second of travel i. The jerk evolution for bicycle and MV was identical within R1 and R2, but R2 yielded in sharp jerk values for these modes. Despite similar in the same roundabout, jerk variation was notably higher for MVs than for bicycles (**Figure 5.4**), especially in the R2. This occurred for three main reasons: 1) low cycling activity; 2) vehicles drive at high approach, circulating and exit speeds (MV average measured speed was 20 km/h and 11 km/h in R2 and R1, respectively); and 3) drivers had sharp acceleration or deceleration to avoid a crash with bicycles.

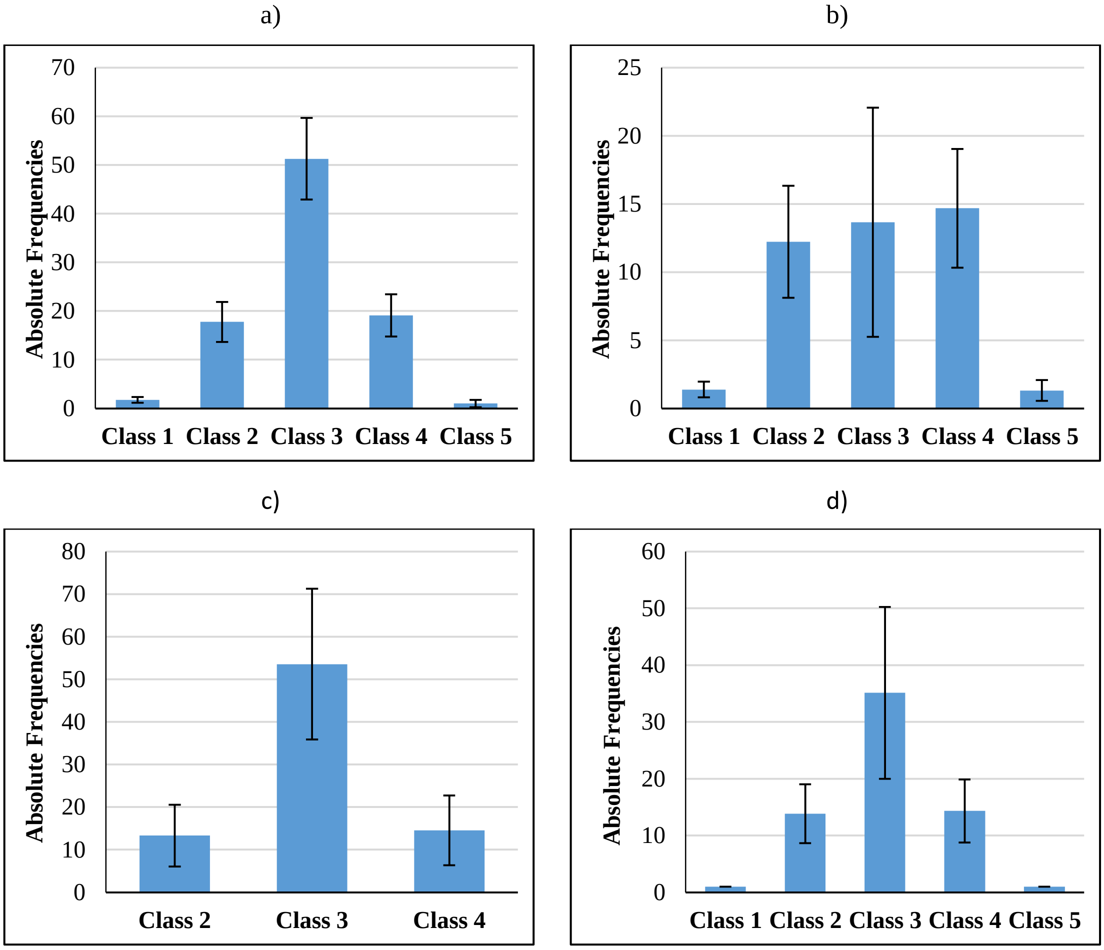


Legend: Dash line is the average jerk value for a speed bin in 1 km/h interval

Figure 5.4. Traffic performance: a) Speed-based volatility of MV at R1; b) Speed-based volatility of MV at R2; c) Speed-based volatility of bicycle at R1; d) Speed-based volatility of bicycle at R2.

5.3.1.2. Acceleration versus Speed

Figure 5.5 a-d represents the time spent in each acceleration class, ranging from high decelerations (class 1) to high accelerations (class 5), according to the previous work conducted by Fernandes et al. (2015) in two-lane roundabouts. It can be observed that vehicles spent 56% of time in acceleration class 3 (-0.2 m.s^{-2} < a < 0.2 m.s^{-2}), and 41% in acceleration classes 2 (-2 m.s^{-2} < a < 0.2 m.s^{-2}) or 4 (0.2 m.s^{-2} < a < 2 m.s^{-2}) in R1. For R2, the percentage in class 3 dropped to 31% while class 2 and 4 contributed together almost 70%. A close look to **Figure 5.5** also confirmed that cyclists had sharper accelerations-decelerations in R2 than R1. For instance, they spent 65% and 29% of time in acceleration class 1, 2, 4 and 5 in R2 and R1, respectively. The size of error bars (standard deviation) values seems to confirm higher variation of values in R2. The Kolmogorov-Sminorv test (two-sample K-S test) confirmed that MVs from R1 and R2 and bicycles from R1 and R2 came from the same distribution at 95% confidence level; D-value were 0.15 (D-critical = 0.29) and 0.08 (D-critical = 0.23) for MVs and bicycles, respectively.



Legend: Class 1 [$a < -2$ m.s^{-2}]; Class 2 [-2 m.s$^{-2} < a < -0.2$ m.s^{-2}] Class 3 [-0.2 m.s$^{-2} < a < 0.2$ m.s^{-2}] Class 4 [0.2 m.s$^{-2} < a < 2$ m.s^{-2}]: Class 5 [$a > 2$ m.s^{-2}]

Figure 5.5. MV Acceleration class by case study: a) MV – R1; b) MV – R2; c) Bicycle – R1; d) Bicycle – R2.

In **Figure 5.6**, all second-by-second MV and bicycle acceleration were plotted against MV and bicycle speed for all trips. R2 covered a wide band of acceleration-deceleration and speed combinations for MV compared to R1. This happened because MVs had sharp acceleration and deceleration rates in R2 compared to R1 as result of some cautions driving (perhaps due to inefficient visibility) on this latter roundabout. Although the range of bicycle values was identical in R2 and R1 (0 to 21 km/h), there was a higher range of variation of acceleration/deceleration at low speed values (< 10 km/h) in the second case study. The field data showed higher MV acceleration-deceleration variation than bicycles did, which is in accordance with previous studies in roundabouts (Silvano et al., 2015).

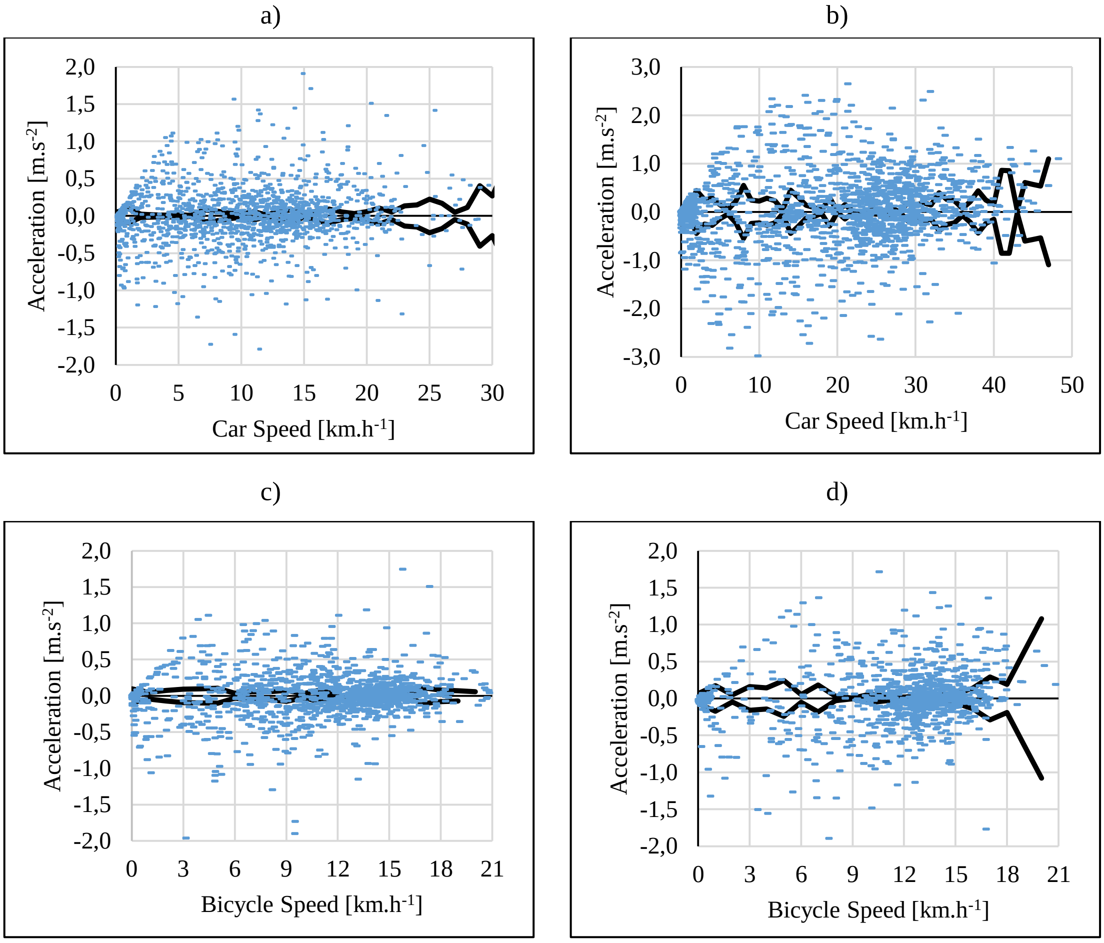


Figure 5.6. Acceleration/deceleration versus speed by mode and roundabout: a) MV – R1; b) MV – R2; c) Bicycle – R1; d) Bicycle – R2.

5.3.1.3. Driving volatility impact on emissions

A relationship between driving volatility and pollutant emissions was conducted (**Figure 5.7 a-b**). Results confirmed that, on average, MVs spent more time in idling (VSP mode 3) in R1 (~36%) than R2 (~19%). However, this latter layout recorded VSP modes higher than 8. To complement the analysis, the Kolmogorov-Sminorv test (two-sample K-S test) was used to assess if the VSP modal distribution between roundabout differed significantly on all routes performed at 95% confidence level. It was found that

D-value was 0.23 (D-critical = 0.24), thereby suggesting a same distribution of R1 and R2 modes distribution.

The comparison of emission for both layouts dictated higher emission per unit distance for R2; CO_2, CO, NO_X, and HC were, respectively, 297 (g/km), 436 (mg/km), 583 (g/km), and 19 (mg/km). Concerning the R1, CO_2, CO, NO_X, and HC were, respectively, 272 (g/km), 370 (mg/km), 517 (g/km), and 20 (mg/km).

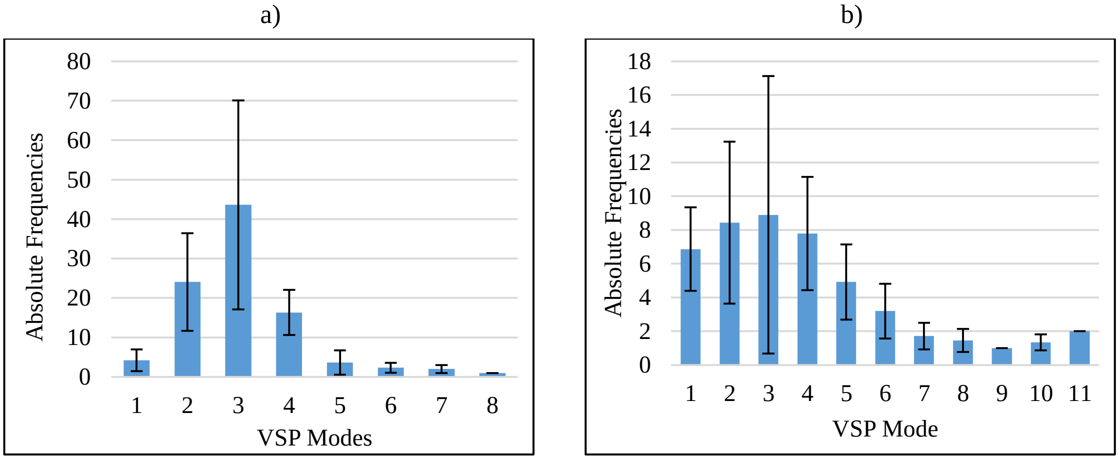


Figure 5.7. VSP modes distributions (with standard deviation) by roundabout a) R1; and b) R2.

5.3.2. Calibration and validation

The calibration and validation of modelling platform was performed on a link-basis. The summary of calibration for the traffic model with adjusted parameters at R1 and R2 (considering the same driving parameters) is presented in **Table 5.2**. A good fit between observed and estimated data was obtained using a linear regression analysis with the values of R-squared (R2) higher than 0.9. With respect to the safety model, SSAM conflicts were computed using the threshold TTC values of 1.5 s at R1 and R2, respectively (R^2 = 0.76 and R^2 = 0.72 at R1 and R2 respectively). Those TTC thresholds yielded the lowest Mean Absolute Percent Errors (MAPE) values between estimated and observed conflicts (15%-R1; 10%-R2).

Regarding the model validation, the average speed of bicycle and MV were conducted using 100 floating bicycles and the MVs (Dowling et al., 2004). The differences between observed and estimated average speeds at a 95% confidence interval were not statistically significant: 1) Speed (R1-MV) (p-value = 0.75); 2) Speed

(R2-MV) (p-value = 0.58); 3) Speed (R1-Bicycle) (p-value = 0.25); and 4) Speed (R2-Bicycle) (p-value = 0.18).

Crash data showed low frequency of annual crashes in both roundabouts, especially those involving motor vehicles and cyclists (ANSR 2019). Therefore, the validation of the modeling platform did not include any validation of SSAM conflicts. For purpose of analysis, traffic conflicts were computed using the default TTC value of 1.5 s, as suggested by F. Huang et al. (2013) in urban areas. VISSIM calibrated parameters in **Table 5.2** were further applied to assess safety on the studied locations.

Table 5.2. Summary of calibration for the traffic model with adjusted parameters at R1 and R2.

Parameter	Value	*GEH*	R^2	MAPE
Average standstill distance (m)	1	< 4 for 95% of the links	Flows (R1-MV) **(0.97)** Flows (R2-MV) **(0.99)** Flows (R1-Bicycle) **(0.95)** Flows (R2-Bicycle) **(0.97)** Travel time (R1-MV) **(0.95)** Travel time (R2-MV) **(0.98)** Travel time (R1- Bicycle) **(0.91)** Travel time (R2- Bicycle) **(0.93)**	Flows (R1-MV) **(2.1%)** Flows (R2-MV) **(0.5%)** Flows (R1-Bicycle) **(3.2%)** Flows (R2-Bicycle) **(4.3%)** Travel time (R1-MV) **(2.2%)** Travel time (R2-MV) **(0.7%)** Travel time (R1- Bicycle) **(6.5%)** Travel time (R2- Bicycle) **(5.1%)**
Additive part of safety distance	1			
Multiple part of safety distance	1.10			
Visibility	95			
Front Gap (s)	0.5			
Rear Gap (s)	0.5			
Safety Distance	1			
Waiting time before diffusion (s)	60			
Min-headway (front/rear) (m)	0.5			
Safety distance reduction factor	0.6			
Maximum deceleration for breaking	-3			

5.3.3. *Driving volatility impact on safety*

The results of safety model (**Table 5.3**) were in line with prior results for driving volatility (Section 3.1) in both case studies. Specifically, R2 recorded higher average speeds for both cyclists and MVs with values 17.1 km/h and 31.3 km/h, respectively. The number of bicycle stops at R2 is 8 times higher than R1, while R2 had nearby 90% more MV stops compared to R1. As suspected, R2 yielded 9 times more conflicts than R1, mostly due to the higher traffic volumes on that site, and it also had more severe conflicts. As long as TTC and PET decreased both the severity of traffic conflict and probability of potential crash increased (Gettman et al., 2008). R1 surprising yielded lower severe potential crashes since MaxS, DeltaS and DR (absolute values) were higher by 12%, 113% and 305%, respectively, compared to R2. This can be explained by high traffic volumes during peak hour which in turn lead to an occurrence of some traffic conflicts at moderate speeds. However, the difference in MaxS was not statistically different between roundabouts (p-value > 0.05) since speed distributions were similar between roundabouts.

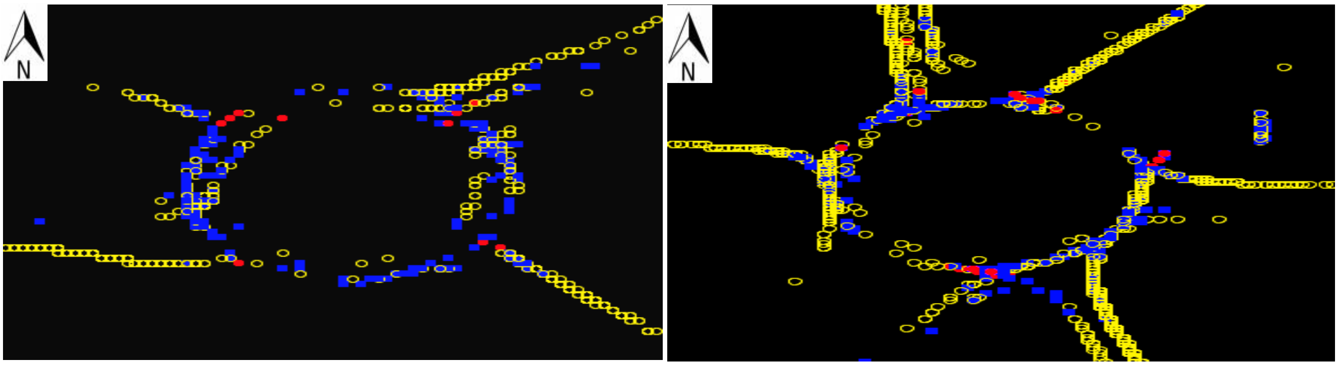
Table 5.3. Comparison between traffic performance and safety at R1 and R2.

Vehicle Class	**Parameter**	**R1**	**R2**	***p*-value**
Motor vehicle	Number (vph)	1,518	1,642	~0.00
	Stops (vph)	812	1,526	~0.00
	Speed (km/h)	27.7	31.7	0.008
Bicycle	Number (n)	251	185	0.002
	Stops (bph)	131	1018	0.16
	Speed (km/h)	12.8	17.1	0.001
Motor vehicles and Bicycles	Total Conflicts (n)	117	1,202	~0.00
	Crossing	1	8	~0.00
	Lane Change	88	1,083	~0.00
	Rear End	28	111	0.002
	TTC (s)	1.2	1.1	~0.00
	PET (s)	1.8	1.1	~0.00
	MaxS (m/s)	5.4	4.8	0.53
	DeltaS (m/s)	3.4	1.6	~0.00
	DR (m/s^2)	-1.6	-0.4	~0.00

Note: *Average values using 10 random seed runs*

Legend: *Shadow cells indicate that the difference between outputs was not statistically significant at 95% confidence level.*

Figure 5.8 depicts the hotspot conflicts location for MV-bicycle and MV-MV in both studied cases. The results showed that conflicts in the approach area were more prevalent (since road users must yield) than the exit area of roundabouts. The number of lane change conflicts was considerable in the circulating areas of R1 and R2 mostly explained by weaving manoeuvres of vehicles before they leave roundabouts to the corresponding exit leg.



a) Conflicts area at R1 b) Conflicts area at R2

(Crossing Conflicts – Red color, Lane Change - Blue color, Rear End - Yellow color).

Figure 5.8. Hotspot conflicts location for the R1 (left) and R2 (right).

5.4. Conclusions and Policy Implications

The results of this research were promising since speed variation and subsequently, acceleration/deceleration variation were showed to have influence on driving volatility for both bicycles and MVs at conventional two-lane roundabouts. However, motor vehicles yielded higher acceleration-deceleration variation than bicycles. It was also demonstrated that the frequency of MV-bicycle and MV-MV conflicts (up to 9 times), emissions per unit distance (9-15%, depending on the pollutant) and number of stop-and-go cycles (up to 8 times for bicycles and 90% for MVs) were higher at the roundabout with high traffic volumes and low cyclist activity.

It is well-known that emissions and acceleration-deceleration rates are intrinsically associated, but this paper takes a step forward and extends the analysis to the acceleration-deceleration variation (jerk) in different speed ranges and volatility impacts at multi-lane roundabouts.

The potential applications of this research can include the development of quantitative surrogate measures for interaction between MV and cyclists at different roundabout layouts. This could be potentially used for proving real-time information for drivers, or warning surrounding cyclists using emerging connected vehicle technologies. This paper also supplied relevant information for transportation experts to better understand how MV-bicycle interactions can influence traffic performance, safety, and emissions at two-lane roundabouts. It must be outlined that this type of roundabout represents specific problems for cyclists, since it allows vehicles to approach and negotiate at high speeds and enabling lane changing and weaving manoeuvres at the circulating and exit areas.

Therefore, future work will be focused on the analysis of this methodology for a larger number of roundabouts with different layouts (single-lane, compact two-lane and multi-lane), sizes and number of entry and exit legs. It is clearly imperative that driving volatility should include the comparison of different accommodation of bicycle in roundabouts (e.g., sharing bicycles with pedestrian or vehicles; dedicated bicycle lanes separated from pedestrian paths and motor vehicle lanes).

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6. ASSESSING THE OVERTAKING LATERAL DISTANCE BETWEEN MOTOR VEHICLES AND BICYCLES – INFLUENCE ON ENERGY CONSUMPTION AND ROAD SAFETY

The main objective of this research is to analyse the impacts of the overtaking lateral distance between a bicycle and a motor vehicle (MV) on road safety and energy consumption at two-lane urban roads.

An on-board sensor platform was installed on a probe bicycle to measure the overtaking lateral distance and dynamic data. The Bicycle Specific Power (BSP) methodology was used to estimate human required power to ride a bicycle while Vehicle Specific Power (VSP) was used for MVs.

The results showed that 50% of overtaking lateral distance were lower than 0.5m in the peak hours. The BSP and VSP analyses for different values of overtaking lateral distance did not result in any relationship between variables. There was a good fit (R^2 >0.67) between traffic volumes and overtaking lateral distance in the peak hours. On average, the MVs energy consumption in the afternoon was 92% higher than the morning peak periods.

6.1. Introduction and objectives

Cycling offers some important financial, health and social benefits to the users and the environment. Accordingly, cycling is increasing day by day in Europe and in the United States (Pucher et al., 2011; 2017). However, traffic safety concerns could be of high importance for cyclists since they might be more vulnerable to be potentially exposed to injuries in a collision than the driver of a motor vehicle (MV) (Van Hout 2008; Götschi et al., 2016).

In 2016, 2,015 cyclists were killed in road crashes in the European Union (EU28) countries, constituting 8% of all road crashes fatalities (EC 2018). In the same year, 840 cyclists were killed in the United States (US) which accounted for 2.2 percent of all traffic fatalities (NHTSA 2018).

Although bicycle-MV crashes are more severe on rural roads compared to the urban areas (Stone et al., 2003; Dozza et al., 2016), the frequency of crashes on urban roads is typically higher. One of the main reasons is due to the high speed and manoeuvrability ability of MVs at rural roads (Stone et al., 2003). MV speed on rural roads is higher than urban areas, while this high speed can increase safety concerns since it may lead to dangerous overtaking manoeuvres (Llorca et al., 2017).

Other authors also emphasized that MV speed is a fundamental risk factor in cyclist safety mainly when a MV overtaking a bicycle (Stone et al., 2003; Debnath et al., 2018). Ata and Langlois (2011) found that the speed of overtaking MVs can affect the lateral distance at urban streets.

Since bicycle size is smaller than MV, it is possible to use more than one bicycle instead of a MV to improve lane use in urban areas. According to the official guidelines from Danish Road Directorate (Van Hout 2008), a 2 m wide oneway cycle path has a capacity of 2,000 cyclists while in reality is able to unroll 5,200 cyclists per hour. However, if cyclists use the same lane as MVs, the overtaking lateral distance between bicycle and MV is a key concern regarding cyclists' safety (Debnath et al., 2018; Feng et al., 2018). The overtaking manoeuvrability of drivers (Chapman et al., 2012) can change the behaviour of other MVs and cyclists such as rapidly braking or acceleration. This can represent some safety challenges, especially in narrow lanes and congested traffic situations.

The minimum standard of overtaking lateral distance (the distance between the overtaking MV and the bicycle) in most of the countries is 1.5 m although it is 1 m in some states of the USA (Llorca et al., 2017). Generally, MVs are required to keep the minimum distance of 1.5 m (Stone et al., 2003; Llorca et al., 2017; Feng et al., 2018) when passing a bicycle. Overtaking lateral distance is the distance between a MV and a bicycle when the driver is driving straight in the adjacent lane to overtake the bicycle on a road (Dozza et al., 2016; Llorca et al., 2017).

It is well-recognized that MV overtaking speed is one of the most important parameters affecting MV-bicycle lateral distance, and therefore, the cyclist safety (Stone et al., 2003; Shackel et al., 2014). Debnath et al. (2018) measured the overtaking lateral distance between bicycles and MVs based on the speed limit at different zones in the State of Queensland, Australia. They found that when the speed limit is between 70-80 km/h and lower than 40 km/h, the overtaking distance variation comply with the law at curved road sections, and on roads with narrower traffic lanes.

Several studies have shown how the lateral distance variation is influenced by infrastructure design (Shackel et al., 2014; Wang et al., 2015; Mehta et al., 2015), MV speed at rural roads (Stone et al., 2003; Llorca et al., 2017) and urban roads (Chuang et al., 2013), and driving behaviour (Duthie et al., 2010; Kay et al., 2014; Feng et al., 2018). However, there is a lack of research to evaluate the relationship between overtaking lateral distance and specific power considering both MVs and bicycles.

Drivers' decision to keep constant speed or instantaneous decisions to change the speed and subsequently acceleration/deceleration (aggressive driving behaviours) can affect energy consumption, pollutant emissions and safety (Wang et al., 2015; Liu et al., 2017). Cyclists have more manoeuvrability than MVs but they are more exposed to damage than a MV during a crash (Van Hout 2008; Götschi et al., 2016).

Although riding a bicycle is a simple activity, it requires more human energy for long distances when a conventional bicycle is used. Due to the long distance travel between origin and destination or road conditions (uphill), a cyclist can feel tired and he/she may not be to use a bicycle (Dill and Rose, 2012). In this context, Mendes et al. (2015) developed a methodology to quantify the expended energy of a cyclist using a conventional bicycle which stands for Bicycle Specific Power (BSP). BSP followed a concept widely used to estimate engine load for MV that is the Vehicle Specific Power (VSP) (Frey et al., 2002). This regressionbased methodology uses dynamic information (speed and acceleration on a second-by-second basis) and topographic conditions (slope) for MV trips.

This paper addressed the impacts of overtaking lateral distance variation between a bicycle and a motor vehicle (MV) on road safety and energy consumption in two urban corridors with variations in cyclist and traffic volumes, and speeds using Global Navigation Satellite System (GNSS) receivers. The main novelty of this paper is the establishment of a relationship between overtaking lateral distance, and BSP, VSP and traffic flow characteristics in different peak hour periods.

The outcome of this work is ultimately to increase the cycling safety at two-lane urban roads by developing a methodology based on the overtaking lateral distance measurements and cyclist/MV energy consumption during the overtaking manoeuvre. Therefore, the specific objectives of this paper are as follows:

- To analyse the driving volatility impact on road safety considering the bicycle and MV overtaking lateral distance variation and acceleration/deceleration varia-tion;
- To assess the relationship between bicycle-MV overtaking lateral distance varia-tion with Vehicle Specific Power (VSP) and Bicycle Specific Power (BSP);
- To assess the impact of traffic volume variation on bicycle-MV overtaking lateral distance variation.

6.2. Methodology

The methodology of this study relies on field measurements and on-board platform of sensors to measure the overtaking lateral distance between bicycle and MVs (**Figure 6.1**). Site-specific operations were characterized using videotaping system and manual counting. Concurrently, second-by-second bicycle and vehicle dynamic data were collected using GNSS travel recorders. After that, VSP and BSP were used to compute MV and cyclist energy used during the peak hours, then correlations between overtaking lateral distance and above variables were explored.

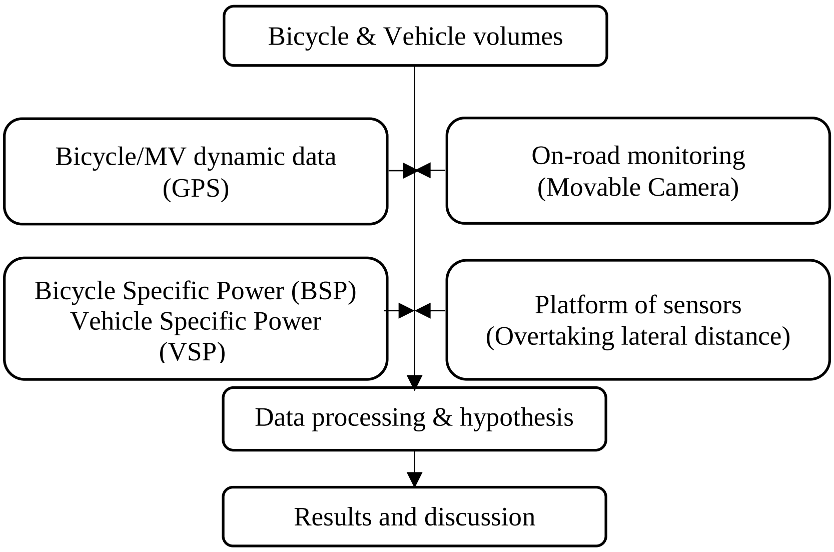

Figure 6.1. Methodological framework.

6.2.1. Instrumented bicycle

The bicycle was instrumented with different sensors and hardware components, as illus-trated in **Figure 6.2.** A microcontroller, ESP8266, was used to control and manage the peripheral hardware. The software was developed and compiled on the microcontroller. This component is able to store and process an instruction from the developed software (User Manual V1.2 2017).

To obtain the real-time location coordinates of the vehicle, a GNSS module named GPS-NEO-M8N was used. The system has low power consumption and small dimensions (25x35mm [boars] + 25x25mm [antenna]), and it can receive a signal from various satel-lite constellations (such as GPS and GLONASS) and follows the NMEA (National Marine Electronics Association) data protocol to communicate with other devices (U-BLOX 2015).

To track the linear acceleration and angular velocity, the motion-processing unit MPU-6050 was used. This device collects and processes the data from its accelerometers and gyroscopes (one for each axis) and stores the output into memories that can read by the microcontroller. The device also has a temperature sensor (InvenSense 2013).

An ultrasonic distance sensor (LV-MaxSonar-EZ1) records the lateral distance of vehicles overtaking by sending ultrasonic waves that are subsequently detected after its reflection in the obstacles. From the time between the sending signal and its echo, the sensor determines the distance to the reflecting object considering the speed of the sound, 340 m/s (MaxBotix 2015).

All the data obtained by the sensors are collected and pre-processed by the microcontroller. Then it is sent to a GSM/GPRS modem (SIM900) that is responsible for the data transmission to the database server through a mobile network, using TCP/IP messages. To be able to connect to the mobile network, a SIM card is required (SIMCom 2010).

This platform of sensors (**Figure 6.2**) can store all dynamic and non-dynamic data in the database server and send it to the end user in real time. The end user can track the cyclist and monitor the bicycle's position and real-time data sent by the sensors. All sensor collected distances that were less than 1.5m. For purpose of analysis, the results are classified into three groups: $x<0.5m$, $0.5m \leq x<1m$ and $1.0m \leq x<1.5m$ ($x<1.6ft$, $1.6ft \leq x<3.3ft$ and $3.3ft \leq x<4.9ft$).

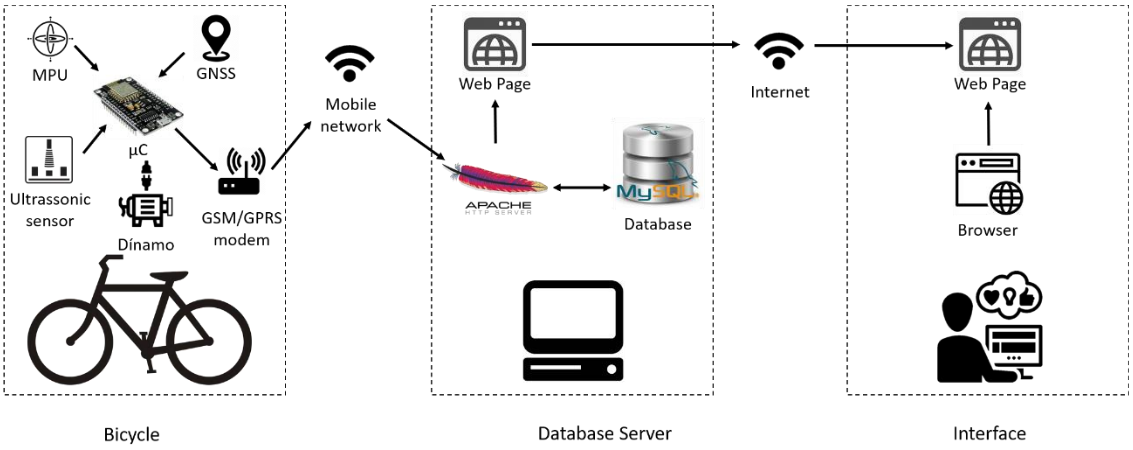

Figure 6.2. On-board platform of sensors for enhancing safety of cyclists.

6.2.2. Data collection and processing

Two case studies with different specifications, such as different average speeds (section 3.2), traffic volumes (**Table 6.1**) and road conditions for both bicycle and MV were selected to develop the methodology in the city of Aveiro, Portugal.

The first case study (A) is a corridor with two-lane urban roads at each direction and four intersections with 4 traffic lights (**Figure 6.3**) that is located in the city centre. This corridor was selected since it connects the train station to the city centre, thus representing a relevant trip generator of MVs and bicycles. Case study A has 760 vehicles per hour (vph) and 26 bicycles per hour (bph) at peak hours. The distance between points A and B is 1.1 km, approximately 4m road width at each direction. Between B and C (~250 m) road has only 3m width with one lane in the travel direction. The second case study (B) is an urban network with four alternative routes (A, B, C and D) between University of Aveiro campus area and one of the city shopping malls (**Figure 6.3**). Traffic movements included two three-leg intersections, one roundabout and four alternative routes. This case study has 460 vph and 10 bph at peak hours. Both case studies A and B are located in a flat terrain.

Table 6.1. Data collection specification for each case study.

Case study A (From point A to point B)		Case study B (from Origin to Destination – 4 routes)	
Average (vph) - AM	536	Average (vph) - AM	328
Average (vph) - PM	984	Average (vph) - PM	592
Average (bph) - AM	22	Average (bph) - AM	9
Average (bph) - PM	30	Average (bph) - PM	12
Total road coverage	55km	Total road coverage	65km
Number of runs	25	Number of runs	23

The sensors, camera and GPS were installed on a conventional bicycle to collect dynamic data and using two different male and female riders between 24 and 37 years old. An equipped light-duty gasoline vehicle with GPS performed several trips along the studied locations where a GNSS device recorded vehicle speed and deceleration/acceleration rates in a 1-second interval. The minimum number of runs (sample size) was 9 for each direction in each case study based on site-specific traffic signal density (<3 traffic lights/1.6 km) (Li et al., 2002). Thus, 40 GPS runs were conducted in this research (20 per site) (Li et al., 2002).

Data were collected in four typical weekdays (Tuesday and Wednesday for each case study) during the morning (8h00-9h30 AM) and the afternoon (5h00-7h00 PM) peak periods. Traffic volumes were counted manually at 5 different points in each direction (**Figure 6.3**) with 15-minute intervals for case study A. For case study B, traffic volumes were recorded manually at the entrance of each route by video recording at two signalized intersections and a roundabout near the destination point of the case study (**Figure 6.3**). As in case study A, the traffic volumes were classified in 15-minute intervals. Driving volatility represents the extent of speed and consequently acceleration/deceleration variations during the MVs movement (Khattak and Wali, 2017).

The speed and acceleration/deceleration profiles of bicycles and MVs were extracted to analyse the driving volatility such as sudden or rapid acceleration/deceleration during bicycle-MV interactions.

Critical and extreme variations can occur due to hard acceleration or braking by drivers (Khattak and Wali, 2017). After identifying these critical points from data, the reason of these behaviours (peak points) was analysed using video recording.

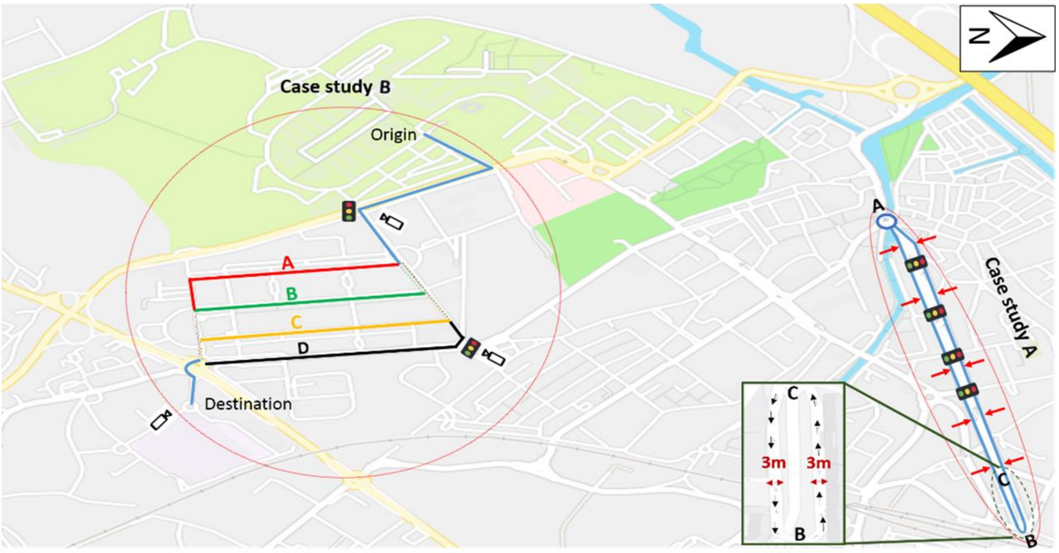

Figure 6.3. Layout of the case study with the identification of traffic monitoring points, case study A (in the left) and case study B (in the right) [Bing Maps].

6.2.3. VSP and BSP data analysis

The selected methodology to estimate the vehicle power consumption variation was based on the concept of VSP that is mathematically defined as follows (Equation 1) (Frey et al., 2002; Anya et al., 2013):

$$\text{VSP} = v.\ [1.1\ a + 9.81\ (a.\tan(\sin(\text{grade}))) + 0.132] + 0.000302v^3 \quad (1)$$

Where

VSP –Vehicle specific power (kW/metric ton);
V_{car} – motor vehicle instantaneous speed (m/s);
A_{car} – motor vehicle acceleration/deceleration rates (m/s^2);
grade – terrain gradient (slope).

Each VSP value refers to one of 14 modes for Light Duty Vehicles (LDV) (**Table 6.2**) which in turn are associated with a rate of energy consumption and emissions (Coelho et al., 2009; Mendes et al., 2015).

BSP is estimated second-by-second using the power needed to ride a conventional bicycle, as given by Equation 2 (Mendes et al., 2015):

$$\text{BSP} = vcyclist\,.\,[1.01\,acyclist + 9.81.sin.(G) + 0.078] + 0.0041vcyclist^3 \quad (2)$$

Where

BSP – Bicycle specific power (W/kg);
$v_{cyclist}$ – Cyclist instantaneous speed (m/s);
$a_{cyclist}$ – Cyclist acceleration/deceleration rates (m/s^2);
G– Road grade (slope).

Each BSP value is divided into 11 modes (**Table 6.2**) that represent one levels of human energy consumption to ride a conventional bicycle. It should be mentioned that the definition of modes and BSP values varied according to the type of bicycle (e.g. electric bicycle, conventional bicycle (Mendes et al., 2015).

Table 6.2. Binning method for VSP in LDV (Frey et al., 2002), and BSP for conventional bicycles (Mendes et al., 2015).

VSP		**BSP**	
Range (kW/ton)	**Mode**	**Range (W/kg)**	**Mode**
VSP < -2	1	BSP < -4	< -4
-2 ≤ VSP < 0	2	-4 ≤ BSP < -3	-4
0 ≤ VSP < 1	3	-3 ≤ BSP < -2	-3
1 ≤ VSP < 4	4	-2 ≤ BSP < -1	-2
4 ≤ VSP < 7	5	-1 ≤ BSP < -0	-1
7 ≤ VSP < 10	6	BSP = 0	0
10 ≤ VSP < 13	7	0 ≤ BSP < 1	1
13 ≤ VSP < 16	8	1 ≤ BSP < 2	2
16 ≤ VSP < 19	9	2 ≤ BSP < 3	3
19 ≤ VSP < 23	10	3 ≤ BSP < 4	4
23 ≤ VSP < 28	11	BSP > 4	> 4
28 ≤ VSP < 33	12		
33 ≤ VSP < 39	13		
VSP ≥ 39	14		

6.3. Results and discussion

In this section, the main results from the field measurements are analysed during the bicycle-MV interactions. It proceeds in four sections: First, the overtaking lateral distances are presented (Section 3.1) followed by acceleration/deceleration profiles

(Section 3.2) and resulting VSP-BSP mode distributions (Section 3.3). Lastly, the hypotheses are defined and tested (Section 3.4).

6.3.1. Bicycle-MV overtaking distance

The extracted data from sensor showed most of the overtaking lateral distance (~75%) occurred in values lower than 1.0 m in both periods (**Figure 6.4**), regardless of the case study. However, the distribution of intervals varied between periods. Regarding case study A, about 56% of bicycle-vehicle overtaking distances were below 0.5 m during afternoon peak but it decreased (in relative terms) in the morning peak (42%). The reason for this result may be due to the differences in traffic volumes between periods (on average, 84% higher in the afternoon peak) that results in less available space for overtaking. Similarly, the results for case study B indicated that about 34% of bicycle-vehicle overtaking dis-tances were below 0.5 m during morning peak hours and increased up to 49% in the after-noon.

It is important to emphasise that frequency of the overtaking lateral distance situations for case study B (~25%) is lower than case study A (**Figure 6.4**). It could be due to lower traffic volumes in case study B compared with case study A.

Another explanation for these distances was due to the location where overtaking occurred. For instance, most of these situations occurred near point B (**Figure 6.3**), which has only one circulating lane by direction. Cyclists should avoid riding close to the right edge of the road while at the same time they should care about the overtaking distance from the left side. This situation can increase the risk of a crash in narrow shared lanes.

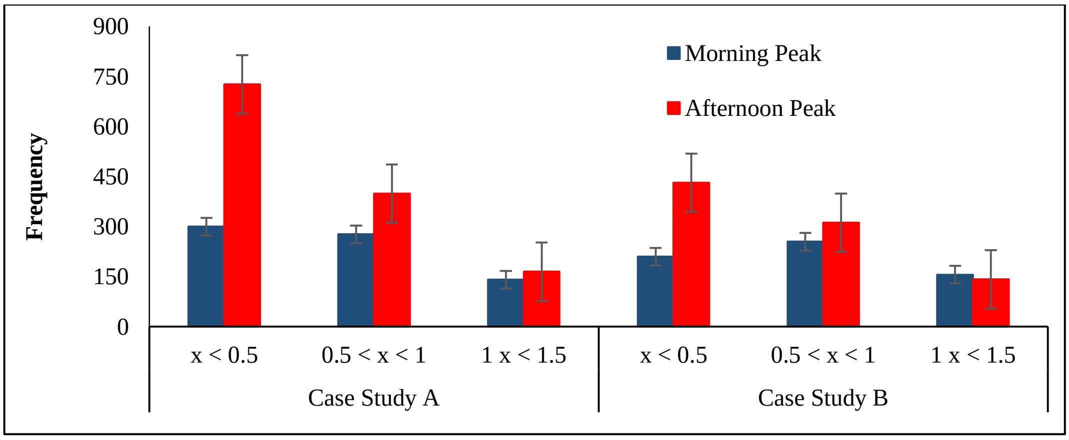

Figure 6.4. Bicycle-MV overtaking distance variation (metres) in morning and afternoon peak hours.

6.3.2. Bicycle-MV acceleration/deceleration profile

Bicycles moving at lower speeds than MVs can have more manoeuvrability to use any part of the lane for safety purposes. The average speed values by mode and case study were as follows:

- MVs in case study A – 20 km/h in the morning peak hour and 17 km/h in the afternoon peak hour;
- Bicycles in case study A – 13 km/h in the morning peak hour and 10 km/h in the afternoon peak hour;
- MVs in case study B – 28 km/h in the morning peak hour; 22 km/h in the afternoon peak hour;
- Bicycles in case study B – 15 km/h in the morning peak hour and 12 km/h in the afternoon peak hour.

The above-mentioned results indicated higher speed values in case study B, regardless of the peak period. This point may be explained by the high volume-to-capacity ratio in case study A (up to 0.65) even though corridor has two lanes in travel direction.

The analysis of the bicycle acceleration/deceleration profiles showed similar profiles within transport mode in the morning and afternoon regardless of the case study. Bearing this in mind, one profile was selected from the morning and afternoon data samples for bicycles and MVs, as shown in **Figure 6.5.** It was found that, regardless of the case study, the range of acceleration/deceleration rates in the morning was higher than in the afternoon. This may be due to the fact that traffic volumes are higher in the afternoon peak periods, resulting thus in more stop-and-go cycles due red signals, pedestrians at crosswalks or yielding to circulating traffic at roundabouts. Other reason behind these peak points of driving volatility is that MVs or cyclists did braking manoeuvres to avoid the crash with those vehicles that were moving from the parking area to the travel lane or because of suddenly opening of the door into the path of the bicycle. There was some evidence that the high bicycle acceleration/deceleration rates were caused by drivers who opened car doors into the path of an approaching cyclist or others who illegally parked MVs at the right-hand side of the road (mainly on the bicycle path).

Riding and driving behaviours of cyclists and drivers were analysed at narrow sections of lanes (250m from C to B and B to C) in case study A (**Figure 6.3**). Travel start and stop times from point C to B were extracted from videotapes using GPS data. The results showed that there is no evidence of high acceleration/deceleration rates and MVs behaviour and manoeuvrability were proper at narrow sections of lanes while the most overtakes of less than 0.5m overtaking lateral distance occurred at these sections of lanes. Cyclists have to pay more attention to left and right sides when the lane is narrow, whereas it seems that drivers also care more about cyclists in these areas.

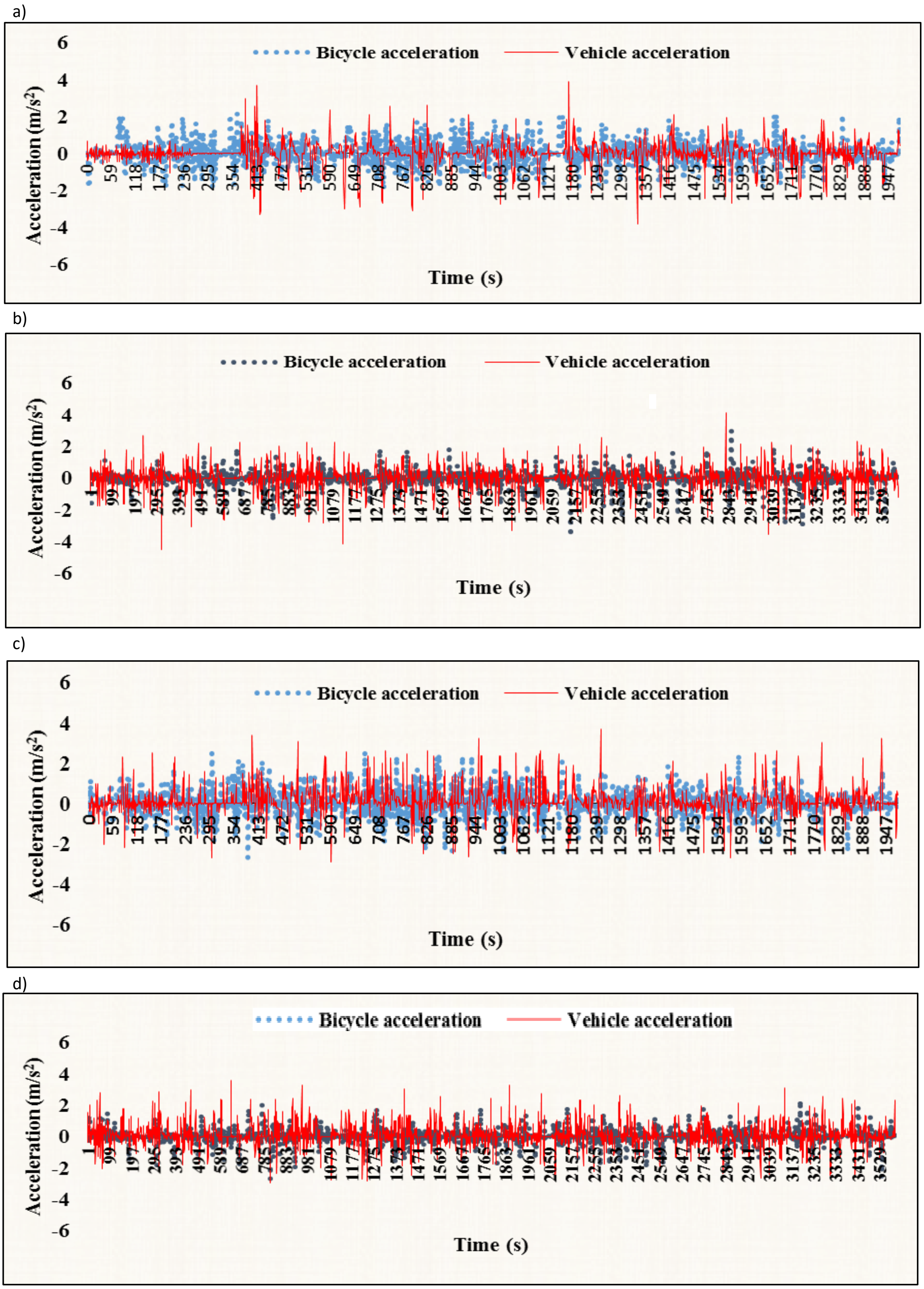

Figure 6.5. Bicycle and MV acceleration/deceleration profiles at peak hours: (a) morning case study A; (b) after-noon case study A; (c) Morning case study B;(d) afternoon case study B.

6.3.3. VSP and BSP mode distribution

VSP and BSP values were calculated against the time spent by MV and bicycle in their modes. **Figure 6.6 a, c** represent the distribution of BSP modes for a conventional bicycle during the peak hours. On average, the bicycle spent more time in mode 1 (50%) than other modes in both morning and afternoon periods regardless of the case study. This finding was confirmed by Mendes et al. (2015) about conventional bicycles. The higher percentage of mode 1 may be since cyclists do not need high human power to ride a bicycle or may be due to the low speeds of bicycles. Regarding the distribution of the modes, no significant differences were observed between the morning and the afternoon peak hours. To examine the consistency between the morning and afternoon VSP mode distributions, the two-sample Kolmogorov-Smirnov statistical test (K-S test) for the analysis of histograms with 99% confidence level was used for both case studies A and B. The mean of BSP values showed only 7% and 9% difference between morning and afternoon in case studies A and B, respectively.

The results confirmed that on positive BSP modes, the bicycle spent more time (83% and 79% in case study A and B, respectively) compared with the negative modes (17% and 21% in case studies A and B, respectively) in both morning and afternoon peak hours. Fig. 6 b, and d represent the distribution of VSP modes for MVs during the peak hours. VSP modes distribution in case study A are approximately same in the morning and the after-noon peak hours while the variation of VSP modes is higher in case study B. It can be due to the more space available for the movement in case study B than A. The average speed of case study B (25.2 km/h) (considering both the morning and afternoon periods) was 34% more than case study A value (18.8 km/h).

MVs spent on average more time in mode 3 (31% and 28% in case study A and B respectively) and mode 4 (27% and 23% in case study A and B respectively) than other modes in both the morning and afternoon peak hours. Mode 3 represents idling and low speed situations while mode 4 represents accelerations at low speeds.

CO_2 emissions were calculated based on VSP concept (Frey et al., 2002) for the gasoline MVs in peak hours in order to assess the energy consumption. Regarding the direct correlation between CO_2 emissions and energy consumption, energy consumption was found to be increased by 92% in the afternoon compared with the morning.

The results showed that 17% and 32% of CO_2 emissions in the morning and 16% and 37% in the afternoon were generated in mode 3 (idling or low speed situations) and mode 4 (acceleration at low speeds) in case study A. About case study B, mode 3 and 4 have corresponded to 14% and 27% of CO_2 emissions in the morning and 12% and 16% in the afternoon in case study B. As shown in **Figure 6.6 b, d**, the frequency of time distribution for modes 3 and 4 was approximately the same in the morning and the afternoon. The mean of VSP values showed only 4%-6% difference between morning and afternoon.

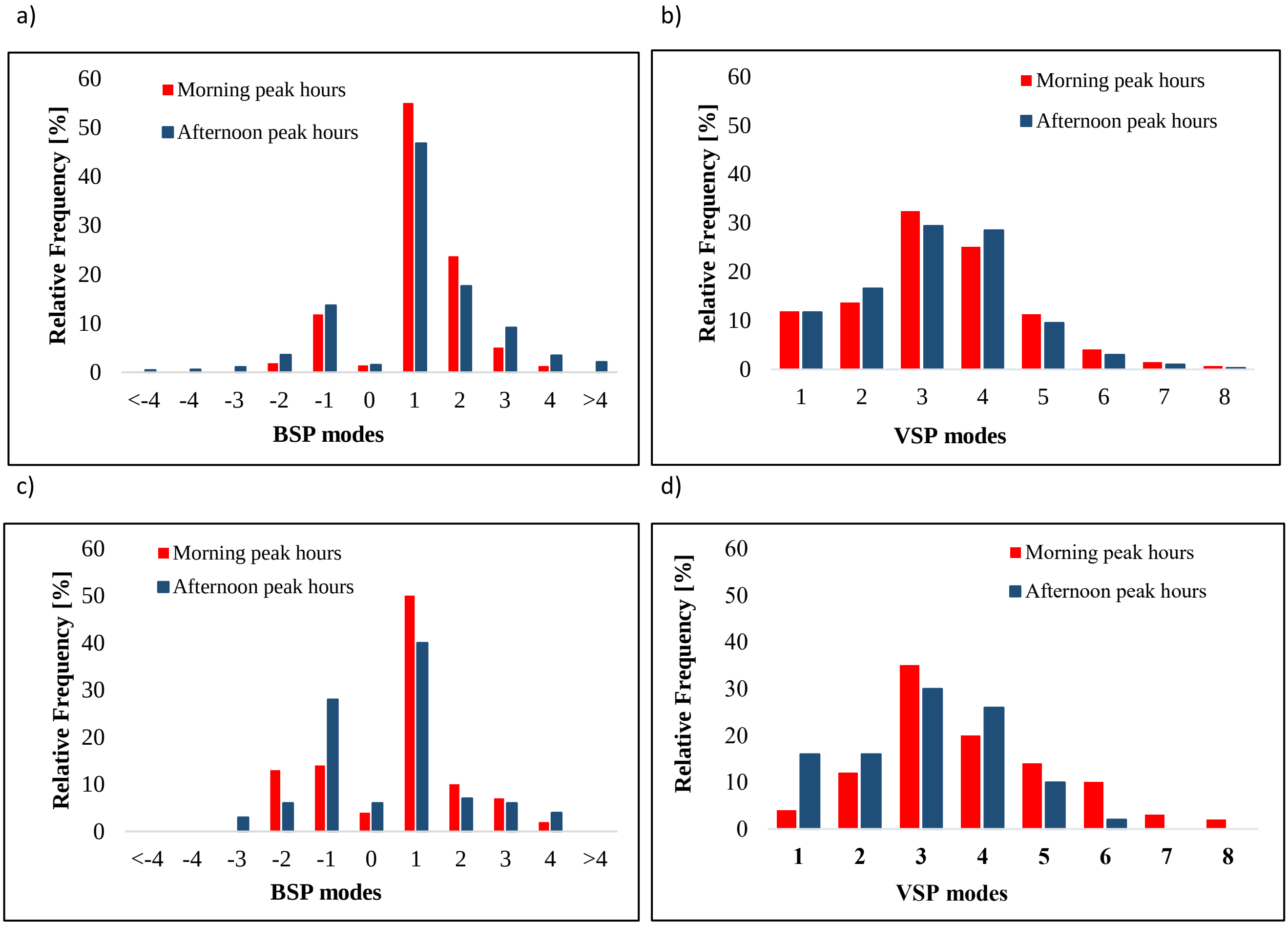

Figure 6.6. (a) Bicycle Specific Power (BSP); (b) Vehicle Specific Power (VSP) modes distribution in case study A; (c) Bicycle Specific Power (BSP); (d) Vehicle Specific Power (VSP) modes distribution in case study B, in morning and afternoon peak hour.

6.3.4. Hypothesis testing

The relationships between overtaking lateral distance and VSP/BSP mode and traffic volume were investigated. The morning overtaking lateral distance values were on average higher than the afternoon period when the traffic volumes were lower.

Therefore, the authors decided to evaluate the impact of traffic volume on overtaking lateral distance variation and the following hypothesis was defined:

- Overtaking lateral distance variation was expected to have less impact on VSP and BSP modes than traffic volumes.

The results from **Figure 6.7** seem to confirm above hypothesis. First, no correlation (coeffi-cient of determination – $R^2 < 0.07$ and $R^2 < 0.02$ in case studies A and B, respectively) was found between VSP/BSP and overtaking distance variation, regardless of the time period.

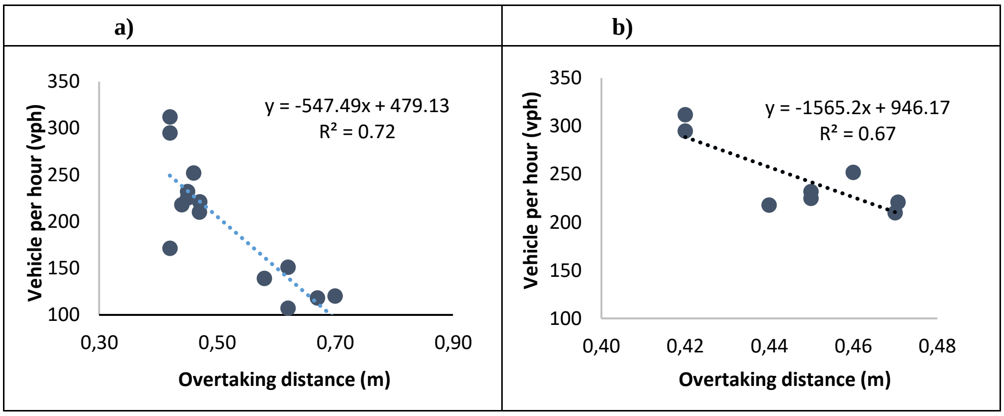

Figure 6.7. Correlation between overtaking distance variation and traffic volume variation: (a) Morning peak hours; (b) Afternoon peak hours.

Second, scatter plots indicated that traffic volumes (15-min intervals) and overtaking lateral distance followed a linear trend both in the morning and afternoon peak hours ($R^2 = 0.72$ and $R^2 = 0.67$ in the morning and afternoon peak hours of case studies A and B, respectively). Both intercept and slope parameters had p-values lower than 0.05, thus indicating statistical significance. **Table 6.3** summarises the statistical analysis of models separately for the morning and afternoon periods.

Table 6.3. Summary of statistical analysis for model coefficients between traffic volumes and overtaking lateral distance variation.

	Period	Model Parameter	*Coefficients*	*Standard Error*	*T statistics*	*p-value*
Case study A	Morning peak	Intercept	946.2	199.7	4.7	0.003
		Variable X1	-1565.2	445.8	-3.5	0.013
	Afternoon peak	Intercept	252.0	43.9	5.7	0.004
		Variable X2	-195.6	72.1	-2.7	0.037
Case study B	Morning peak	Intercept	736.21	217.6	3.1	0.011
		Variable X1	-423.3	332.1	-2.2	0.004
	Morning peak	Intercept	317.1	100.5	3.8	0.002
		Variable X2	-1205.4	215.3	-4.1	0.027

Results from **Figure 6.7** and **Table 6.3** confirmed that the traffic volume variation had a moderate effect on overtaking lateral distance between bicycles and MVs during the peak hours. Regardless of the case studies, it can be concluded that overcoming lateral distance between the bicycle and the MVs decreases with increasing traffic volume.

Since the traffic volumes were collected at different segments of case study A and at different routes of case study B, the results of correlation between overtaking lateral distance and traffic volume variation can be applied to all the corridor (case study A) and the network (case study B). The linear coefficient model within a 95% confidence level was applied to show the relationship between traffic volumes and overtaking lateral distance. Variable Y represents the overtaking lateral distance while X1 and X2 represent traffic volumes in the morning and afternoon periods, respectively.

6.4. Conclusions

This research represents an evaluation of the impacts of the bicycle-MV overtaking lateral distance on driver and cyclist behaviours, safety and BSP/VSP mode distributions. Field measurements were conducted in a real-world corridor with traffic lights and an urban network with four alternative routes. The analysis was based on overtaking lateral distance measurements extracted from a platform of sensors installed on a conventional bicycle. Measurements were carried out in morning and afternoon peak hours. Bicycle and MV GPS data were also used to characterize road user behaviours.

More than 75% of the total overtaking lateral distances were lower than 1 m, and 50% were lower than 0.5 m, thus confirming some issues regarding the cyclist safety. It was found that lowest overtaking lateral distances (<0.5 m) occurred in segments with high traffic volumes segments with resulting lack of road space during the interaction between motor vehicles and cyclists. The analysis of acceleration/deceleration profiles confirmed that bicycles and MVs had similar behaviour in both periods, but the trend of acceleration/deceleration for MVs was higher than bicycles regardless the case studies.

The analysis of relationship for traffic volumes and overtaking lateral distances showed moderate to good fit between these variables (R^2 = 0.68 and R^2 = 0.73 for case studies A and B respectively). In contrast, no correlation was observed between overtaking lateral distance and bicycle-MV overtaking lateral distance.

Although dynamic data used in this paper was stored before processing, one of the main contributions of this paper is the integration of real-time driving volatility information on a platform to alert road users about potential proximity with cyclists, and as result, some crashes.

Future study would consider the impact of age, gender or colours of clothes of cyclists on overtaking distances, and different types of road.

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7. CONCLUSIONS AND FUTURE RESEARCH

This chapter of the thesis reports the contribution of the developed research in Section 7.1 followed by summary of main conclusions in Section 7.2. Section 7.3 outlines the main research limitations followed by future work recommendations in section 7.4.

7.1. Contribution of the research

The main contribution of this PhD thesis focused on the assessment of the driving volatility and the impacts of the MV-bicycle interactions at urban areas considering multi-objective criteria. The thesis developed a multi-objective model for bicycle and MV users to choose the proper route based on traffic performance, emissions and safety concerns. The parameters concerning the MV and bicycle activity data (speed, acceleration-deceleration), traffic volume, energy consumption and overtaking lateral distance were characterized in detail. The candidate studied locations were located in an urban areas and they included different traffic control treatments such as traffic lights, stop-controlled intersections and conventional roundabouts.

Although extensive research was carried out about interaction of MV-bicycle in different type of roads and traffic conditions, there are few studies about impacts of MV-bicycle interaction on the traffic performance (such as travel time, speed, traffic flow and number of stop-and-go), pollutant emissions (CO_2, CO, NOx, and HC), and safety concerns (such as number of traffic conflicts and TTC). Furthermore, while most of the multi-objective studies in traffic engineering have been used two-dimensional optimization methods, only a few studies have focused on three-dimensional or more than three-dimensional solutions. Most of the multi-objective models used different bi-objective or single objective models in order to simplify the calculations. These models cannot optimize several objectives simultaneously.

To accomplish the posed objectives, several empirical and simulated-based studies were carried out in the selected studied locations. The main contributions of the thesis are as follows:

- Chapter 1 addressed the importance of cycling in urban areas, aspects regarding safety issues experienced by cyclists, the relevance of multi-objective in transport-related problems, multiple impacts of interaction MV-bicycle (traffic performance, emissions and safety), and the questions and objectives of the thesis. Furthermore, this chapter emphasized the existing gaps and multi-objective decision-making tools from a comprehensive literature review in the field study of the thesis.

- Chapter 2 develops an overview of the main methodology and methods used in the next chapters.
- Chapter 3 provided a multi-objective tool to assess the safety of cyclists, traffic performance and emissions based on the bicycle demand variation at three-leg intersection with traffic lights. The novelty of this paper is the analysis of cyclists' demand effects at the intersection influence area on traffic performance, emissions and conflicts between motor vehicles and cyclists. Also, this research identifies some trade-offs among the outputs.
- Chapter 4 extended the developed multi-objective model for passengers in routing choice problems by taking into account traffic performance, pollutant emissions, and safety criteria. This chapter explores the lack of research using multi-objective analysis to find balanced solutions on above criteria on an integrated way for both cyclists and motor vehicle drivers. Furthermore, a crash reconstitution model was used to explore the cyclist safety in aforementioned intersection considering the MV-bicycle interaction. The contribution of this part focused on cyclist safety considering the impact of MV velocities variation beside some important parameters such as collision angle, collision speed and shape of the car.
- Chapter 5 explores the impacts of driving volatility in MV-bicycle interactions at two-lane roundabouts on safety, pollutant emissions and traffic performance.
- Chapter 6 assess MV overtaking maneuvers of bicyclists in an urban environment two-lane road with traffic signals. The contribution of this chapter is to understand how traffic volumes variation may impact overtaking distance and investigate the relationship between VSP, BSP, and overtaking distance.

7.2. Summary of the findings

7.2.1. General findings

The presence of bicycles may dictate a trade-off between traffic performance, emissions and safety outputs. In this way, multi-objective optimization can be a useful tool in order to make a balance among outputs. The results showed that two-lane roundabout outperformed the existing fixed time signal control. The impacts of bicycle demand were mixed for traffic, emissions and safety. The presence of bicycles increased the number of stop-and-go for motor vehicles and also increased the delay when the bicycles demanded exceeded the optimal number at the intersection. The results of multi-objective analysis delivered an optimal bicycle demand lower than 165 bicycles per hour taking both environmental and safety points of view. Implementation of two-roundabout instead of the intersection improved intersection-specific traffic performance and pollutant emissions regardless of the number of bicycle users, but the safety benefits of this layout were less pronounced under high-bicycle demands (more than optimum bicycle demand at each roundabout).

Regarding multi-objective optimization for short distance trips, the results showed that a bicycle can replace a MV in the selected urban network. The results of this replacement were more significant on routes with less capacity and traffic volumes, and so that traffic conflicts between MV and cyclists. By implementing a dedicated lane for bicycles, all the traffic performance, emissions and safety concerns improved. In most of the routes, a bicycle was faster than MV.

The interaction between MVs and bicycles at two-lane roundabouts confirmed a good correlation ($R^2 > 0.70$) between acceleration variation and VSP modes distributions. Most of the acceleration/deceleration variation occurred at the high-sized roundabout without dedicated bicycle lane. It was also found that geometric specification of each roundabout, design and shape affected traffic performance, emissions and safety concerns for cyclists and drivers.

The analysis of the relationship between traffic volume and overtaking distance showed good correlation between lateral overtaking distance and traffic volumes at two-lane roads. It was found that on average the energy consumption in the afternoon was 92% higher than the morning. However, no evidence of relationship between overtaking distance variation (between bicycles and MVs) and human/vehicle energy consumption were observed.

7.2.2. Specific findings

Chapter 3: *Cycling at intersections: A multi-objective assessment for traffic, emissions and safety*

- Comparing the results of implemented roundabout instead the fixed time traffic light, it was found that the number of stops and travel time reduced by 78% and 14%, respectively; 7%-12% fewer emissions, depending on the pollutant;
- As the number of bicycles increased from 9 to 270 bicycles, the emissions generated by vehicles reduced (on average 9%, 6%, 6% and 8% for CO_2, CO, NO_X and HC, respectively), and concomitantly the travel time increased about 5% for the motor vehicles;
- Number of conflicts was reduced (-49%) after roundabout replacing traffic light even in maximum bicycle demand scenario (270 bicycles per hour).

Chapter 4: *Multi-objective optimization for short distance trips in an urban area: choosing between motor vehicle or cycling mobility for a safe, smooth and less polluted route*

- The results showed that there is only ~15% difference between MV travel time (401 s) and bicycle travel time (461 s) on the shortest route of the network.
- Regarding the cyclist safety, the longitude cyclist head impacted location on the vehicle to the front of the vehicle when the velocity impact is less than 45 km/h and more than 60 km/h (maximum 81 km/h), is longer than when velocity impact is between 45 km/h and 60 km/h. This means that the high speed of a vehicle may lead to less injury for a cyclist than low speed because the cyclist head impact location also depends on other parameters such as collision angle and shape of the vehicle.

Chapter 5: *Interaction between motor vehicles and bicycles at two-lane roundabouts: a driving volatility based analysis*

- Most of the acceleration/deceleration variation occurs when the speed was higher than 27 km/h and 38 km/h, respectively, at R1 (small roundabout) and R2 (high roundabout) for both bicycles and MVs.
- R2 recorded higher average speeds for both cyclists and MVs with values 17.1 km/h and 31.3 km/h, respectively. Also, the number of bicycle stop at R2 is 8 times higher than R1, while R2 had nearby 90% more MV stops compared to R1.
- The number of bicycle stop at R2 is 8 times higher than R1, while R2 had nearby 90% more MV stops compared to R1.
- R1 had lower severe potential crashes since MaxS, DeltaS and DR (absolute values) were higher by 12%, 113%, and 305%, respectively, compared to R2. This can be explained by HDV traffic at that drive at lower speeds, leading to an occurrence of traffic conflicts at moderate speeds.

Chapter 6: *Assessing the overtaking lateral distance between motor vehicles and bicycles – impacts on energy consumption and road safety*

- There was a good fit between BSP/VSP and traffic volumes in the morning ($R^2 = 0.68$) and afternoon ($R^2 = 0.73$) peak hours.
- It was found that the cyclist spent more than 80% of time in Positive BSP modes, regardless of the peak hour period.

7.2.3. Implementation contributions

The findings of this thesis can be helpful for cyclists (in different range of the age) and drivers with own route choice criteria, short distance trips. This multi-objective tool allows to transportation network designers to improve the network by balancing all the important objectives simultaneously.

From the point of view of infrastructure management, an optimization signal time of traffic lights is not the unique way to improve the traffic performance at signalized intersections, sometimes by considering a dedicated lane for bicycles/MVs or changing the design of the intersection can improve the results of traffic performance, emissions and safety.

Including the role of the bicycle in driving volatility assessment can lead to achieve real results of the traffic performance, energy consumption and safety concerns at different type of roads. The impact of driving volatility mainly on safety concerns is more related to the design of the intersections and traffic roads. The findings of this research can give some guidelines to researchers and transport engineers in order to pay more attention for the spaces and traffic lane specifications. The findings can be also useful for route choice analysis based on data, applications, models and algorithms not only with regard to MV drivers' behavior but also with regard to cyclists' behavior. The findings also may be useful for improving traffic external cost methodologies based on MV-bicycle interactions at urban areas.

During this doctoral program 6 articles in scientific journals (5 published and 1 submitted), 1 book chapter and 11 papers in international scientific confrences (10 published and 1 submitted) were extracted in line with the goals and objectives of this thesis.

7.3. Limitations

The following limitations are identified:

- Most of the research study was conducted in short time periods (e.g., one in the morning; one hour in the afternoon).
- All Monitoring campaigns were conducted only in dry weather.
- In this research, VSP method was considered for emission estimation and the archived results cannot represent the real data.
- The used bicycle in the case studies was a conventional bicycle.
- Given the increasing deployment of connected and autonomous technology, a possible future work would be to study the interaction of these vehicles with conventional motor vehicles and vulnerable road users such as pedestrians and cyclists. The main idea will be to develop an integrated research using advanced algorithms in order to reduce driving behavior volatility considering emissions and safety concerns in a connected vehicle

environment. Sensitivity analysis of driving behavior based on the detailed data about speed and acceleration/deceleration variation can be taken into account in order to driving volatility assessment.

- The findings of this research about roundabouts (mainly about the impact of design on emissions, traffic performance and safety) can be generalized to the similar ones not any type of roundabout.

7.4. Recommendations for Future Work

- It would be adequate to extend the same methodology in non-peak periods.
- Different weather conditions (mainly rain) can affect the achieved results. It would be interesting to find the difference of the results comparing the rainy and dry weather situation. In this case, different level of rain must be defined in the methodology in order to classify the results based on the different rainfall intensity.
- Since this research was focused on a three-leg intersection with specific traffic demand patterns, further studies are needed about different types of intersections before generalizing the same results.
- It would be better to use another empirical method and equipment such as PEMS in order to explore the real-time emissions and to compare the results of PEMS versus simulation (VSP).
- There is a need of more research with regards to the simulation of several collisions and conflicts between different types of MVs and bicycles at different roads in order to better explore the cyclist safety concerns at the selected case study.
- It would be adequate to extend this study considering sensitivity analysis with more parameters such as different age groups and gender of cyclists, and different types of road.