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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

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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 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 paper 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.
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 (NO_X) 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).

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Keywords: Microscale modeling, Multi-objective optimization, Traffic, Safety, Emissions

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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 paper 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.

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 the VISSIM after calibration and validation. The flowchart of methodology was illustrated in Fig. 1.

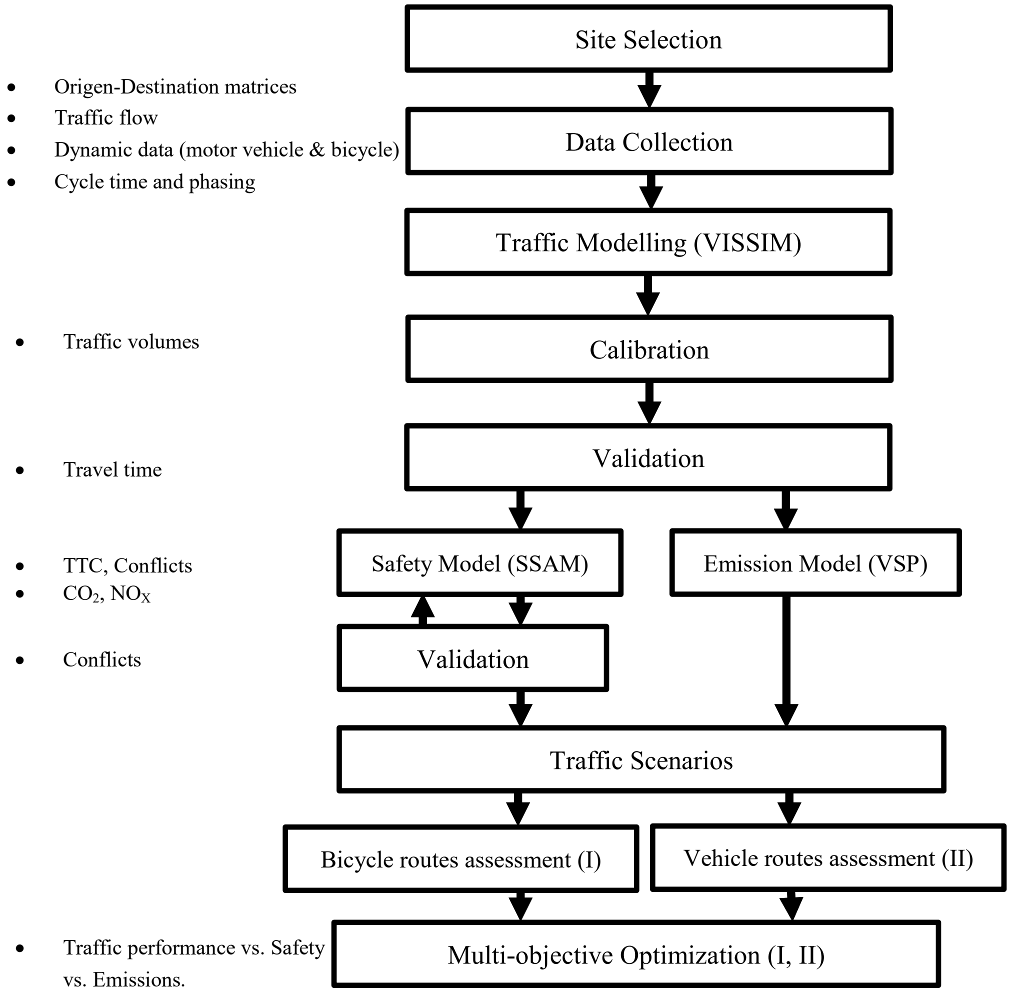

Fig. 1. Methodological framework.

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.

Traffic movements (included two three-leg intersections, one roundabout and four alternative routes, see Fig. 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.

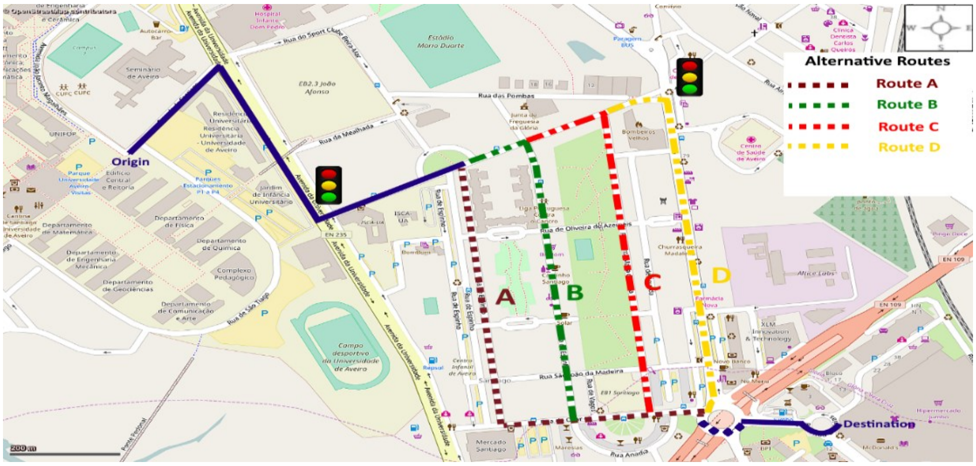

Fig. 2. Layout of the case study.

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):

$$VSP = v.\,[1.1\,a + 9.81\,(a.\tan(\sin(grade))) + 0.123] + 0.000302v^3 \quad (1)$$

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.

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 (Fig. 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.

3. Results and discussions

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 (Fig. 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 (R2 = 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 Fig. 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 (Fig. 3).

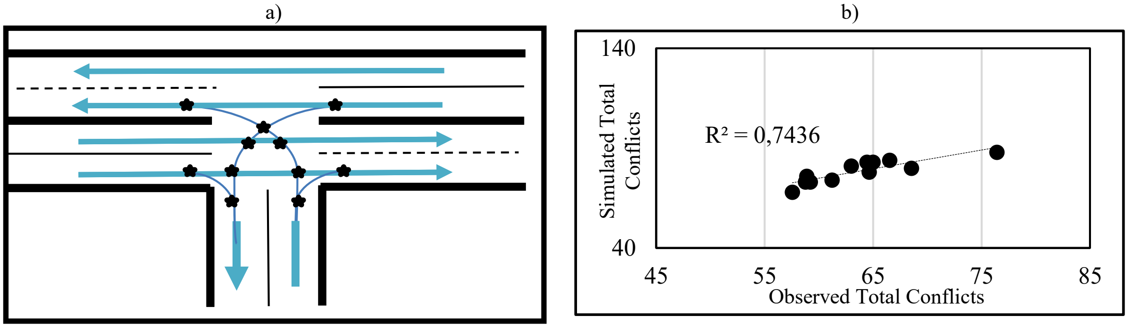

Fig. 3. a) Conflict types observed at three-leg signalized intersection; b) Relationship between observed and simulated conflicts.

3.2. Results of alternative scenario

The summary of results regarding traffic performance, safety and emissions is represented in Table 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 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

3.3. Multi-objective analysis

The previous findings (Table 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.

Fig. 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 Fig. 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.

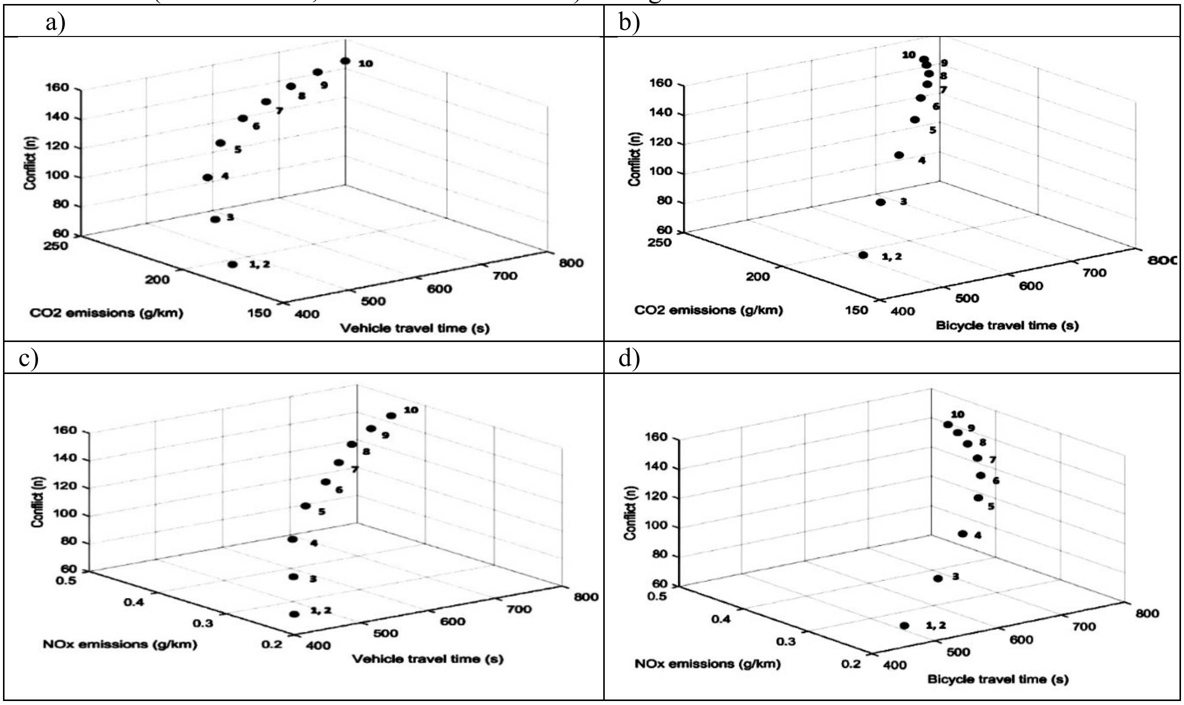

Fig. 4. The approximate final Pareto front: a) Travel time, CO_2 and Conflicts for motor vehicle users; b) Travel time, CO_2 and Conflicts for bicycle users; c) Travel time and NO_X, Conflicts for motor vehicle users; and d) Travel time, NO_X and Conflicts for bicycle users.

For instance, adopting a solution number 6, from Fig. 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 Fig. 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. Conclusions

This paper 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.

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