How to evaluate the extent of mobility strategies in traffic operations benefits: An integrated traffic performance, emissions, safety and costs analysis in a University Campus

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ABSTRACT

This research explored the integrated effect that several mobility scenarios had on traffic performance, conflicts, global and local pollutants, and emission-related costs on a University Campus. An emphasis was given to the campus parking areas. One of the main contributions of this study was the identification of hotspot in terms of emissions, costs and traffic conflict locations.

A well-calibrated and validated modeling platform of traffic, emissions and safety was used to examine different traffic scenarios in the University of Aveiro, Portugal. These included the replacement of traffic lights by roundabouts, direct access to campus and some parking areas, increasing campus walkability and introduction of speed humps on main crosswalks. The analysis was performed both link-by-link and in the overall study area.

Mobility scenarios with a new direct access to the campus yielded average reductions up to 9% in both costs and local pollutants (carbon monoxide, nitrogen oxides and hydrocarbons), and 36% and 32% for the number of stops and traffic conflicts, respectively. Nonetheless, additional traffic conflicts can be expected within campus after the implementation of those scenarios compared to the existing situation.

Keywords: Modeling, Integrated Analysis, University Campus, Mobility Measures, Parking.

INTRODUCTION AND RESEARCH OBJECTIVES

University campuses are places where people arrive daily in individual cars causing occasionally congestion and large amounts of pollutant emissions. They have unique trip characteristics that require special attention in the planning of medium- and large-sized road networks. Specifically, there is a significant percentage of trips using different transportation modes and resulting problems regarding parking spaces (**S. Huang, Guo, Yang, Casas, & Sadek, 2012; Huayan, Wenji, & Haijun H., 2007**). Undoubtedly, as campus enrollment increases, the campus-specific traffic demand also increases, leading thus to a decrease in parking capacity (**Browder, Chimba, & Boykin Jr., 2014**).

Universities embody a cross section of the population from different socio-economic ages and backgrounds, daily commuting, and the predominance of private car use over soft modes of mobility (**Miralles-Guasch & Domene, 2010**). Transportation has been generating a principal concern in University policies. Along with environmental, safety and accessibility concerns, these policies must providing mobility without affecting campus qualities and avoiding wider environmental and social impacts (**Miralles-Guasch & Domene, 2010**). In a study on emissions at university campus by **Juchul, Gyoungjun, and Kyungwan (2016)**, road transportation accounted for 21% of carbon emissions in Pusan National University (South Korea) making it the second highest contributor after building's electricity. In turn, about 40% of total carbon emissions produced in the San Diego State University (SDSU) between 2014 and 2015 came from campus related travel (**Appleyard, McKinstry, & R. Frost, 2017**).

Despite universities are significant generators of pollutant emissions, they can encourage comprehensive set of policies for more sustainable transportation. In this context, a good deal of research looks at Transportation Demand Management (TDM) as an effective way to solve the imbalance of transportation demand in university campuses as well as to fight against private car dependence (**Akar, Flynn, & Namgung, 2012; Appleyard et al., 2017**). TDM seeks to change individual travel behavior which can be determined by structural (e.g., distance, time, cost, road characteristics, public transport services) and individual (e.g., trip purpose, work schedule, time constraints) variables, environmental or social concerns and demographic conditions (**Miralles-Guasch & Domene, 2010**).

The estimation of transportation-related emissions along campus has been carried out by several universities (**Appleyard et al., 2017**). The development of a comprehensive travel survey to all university affiliates is one of most widely-used methods (**Appleyard et al., 2017; dell'Olio, Bordagaray, Barreda, & Ibeas, 2014; Longo, Medeossi, & Padoano, 2015; Popovich, 2014; Welch, 2015**) since it allows measuring mode split and commuting frequency. **Mathez, Manaugh, Chakour, El-Geneidy, and Hatzopoulou (2013)** estimated transportation-related greenhouse gases (GHG) emissions in McGill University campus (Canada) based on gender, travel mode, season and affiliation using a GIS platform. Given the effort in defining and assessing campuses mobility, **Longo et al. (2015)** applied a model based on an Analytic Hierarchy Process (AHP) to investigate the user preferences structure of University of Trieste (Italy). The main user concerns and with potential to be improved were regarding the campus parking and bicycle facilities.

There are some online tools for estimating university transportation emissions such as Sustainability Indicator Management and Analysis Platform (**UNH, 2017**) or the California Climate Action Registry (**CCAR, 2017**). **Appleyard et al. (2017)** used a web-based Campus Carbon Calculator to estimate and compare campus GHG emission from six policy scenarios in the SDSU. It was found that telecommuting and on-line eLearning decreased emissions up to 21% compared to the existing conditions. Encouraging active modes for individuals who live inside campus only reduced emissions in 2%. Complementary, the five-year

European Network for Sustainable Mobility at University (U-MOB LIFE) project began in 2016 with the main goal of integrating all best practices in sustainable mobility on university campuses. The U-MOB expected to accomplish three major goals: *i*) 10,000 campus carbon dioxide (CO₂) emissions surveys; *ii*) 10 action plans identifying mobility best practices; *iii*) 5% reduction in CO₂ emissions on 30 participating campuses until 2021 (U-Mob, 2017).

Little research has objectively addressed the operational issues and environmental impacts related to transportation on campuses. **S. Huang et al. (2012)** used TRANSIMS to estimate the dynamic 24-hour demand in the University at Buffalo. The study included a procedure for parking lot ‘desirability’ ranking, based on voluntarily data such as building occupancies and published class schedules. However, the analysis discarded emission and safety impacts.

The assessment of factors impacting travel mode on campus parking areas has been attracted attention, as evidenced by several published work (**Bridgelall, 2014; Elliott, Jayachandran, Kumar, & Metzger, 2013; Fries, Chowdhury, & Dunning, 2012; Guo, Huang, & Sadek, 2013; Jung, Ha, & Park, 2017; Moradkhany, Yi, Shatnawi, & Xu, 2015; Proulx, Cavagnolo, & Torres-Montoya, 2014**). **Fries et al. (2012)** used a dynamic traffic assignment on a campus parking area, but the research was centered on vehicle delay. **Elliott et al. (2013)** designed the transportation system and parking demand of the George Mason University area from 2012 to 2020. The study focused on the prediction of shuttle ridership and its resulting utility (based on CO₂ and cost criteria), but did not include the impacts on local emissions and safety levels. **Guo et al. (2013)** integrated TRANSIMS and MOVES2010 emission model to develop an agent-based model for University at Buffalo north campus. They found that vehicles wasted 120 gallons of gasoline daily and produced 40% more emissions in the parking search process. However, the emission methodology ignored the variations in vehicle acceleration-deceleration rates.

The above studies offered a variety of methods for inventory emissions from road transportation in campuses, and proposed solutions for improving sustainability in campus design and planning. However, the following gaps were revealed: *a*) all studies failed to offer positive evidence of the influence of specific measures on emissions, traffic performance and safety simultaneously; *b*) little is known about parking access activity on above outputs and campus emission costs as well.

This paper addressed the integrated effect that different mobility scenarios had on traffic performance, global (CO₂) and local pollutant (carbon monoxide – CO, nitrogen oxides – NO_x) emissions, traffic conflicts and emission-related costs on a University Campus. The proposed approach combined a methodology for estimating emissions (Vehicle Specific Power – VSP) and traffic conflicts (Surrogate Safety Assessment Model – SSAM) with detailed microscopic traffic simulation modeling, using the “Verkehr In Städten SIMulationsmodell” (VISSIM). To implement this methodology, the research team selected the campus of the University at Aveiro, Portugal.

Three major features that give novelty to this research: *i*) it includes a practical methodology for estimating costs on a University Campus road network link-by-link; *ii*) it demonstrates that the modeling approach can replicate a wide range of mobility scenarios; *iii*) it explores each scenario-specific benefits and issues by identifying the hotspot in terms of emissions, conflicts and costs locations along the campus.

The second section describes the methodology used in this paper. Information about campus travel patterns, data collection, and traffic, emission and safety modeling are carefully explained. Third section presents the main results from mobility scenarios implementation, and identify the main operational, environmental and safety issues concerning the campus travel activity. This paper finishes outlining the main conclusions and limitations derived from the study and providing ideas for future research (Fourth section).

METHODOLOGY

This research used an approach that combined an emission methodology (VSP) and safety model (SSAM) with a microscopic traffic model (VISSIM). It proceeded in the following steps (**Figure 1**): *i*) to collect traffic, vehicle dynamic and crash data in a real-world University Campus; *ii*) to model campus-specific traffic operations; *iii*) to calibrate and validate the modeling platform; *iv*) to estimate emission costs for each link; *v*) to implement several mobility scenarios; and *vi*) to extract data outputs and then compare the benefits of each measure over existing campus situation. Each step will be explained in detail in the following sections.

Figure 1 Overview of the proposed methodology.

Traffic Modeling

The microscopic traffic model VISSIM 5.40 is selected to model campus-specific operations (PTV AG, 2011). Four explanations supported this choice: 1) defining a wide range of vehicle parameters (e.g., speed, power and weight distributions, size, occupancy, among others) for different transportation modes; 2) including a dynamic traffic assignment

algorithm for parking-based route choice for a large number of parking spaces, as is the case of University Campus; 3) calibrating different driving behavior parameters (car following, gap acceptance and lane change) to set realistic representations of the traffic; and 4) storing individual vehicle trajectory files that can be used to evaluate emissions and safety as well to estimate emission costs (PTV AG, 2011).

A good deal applications was conducted in medium- and large-sized urban networks using VISSIM, namely: traffic restriction measures (Al Eisaia, Moridpourb, & Tay, 2017; Paulo Fernandes et al., 2016), eco-routing (Garcia-Castro, Monzon, Valdes, & Romana, 2017), traffic management strategies (K, Shankar, Prasad, & Reddy, 2013) or design and planning of parking areas (Fries et al., 2012; Yuan & Liu, 2014).

Emissions Modeling

VSP is a microscopic methodology that allows estimating instantaneous power per unit mass of vehicle taking into account aerodynamic drag, speed, acceleration, road grade and rolling distance effects (US EPA, 2002). VSP is a function of speed, acceleration-deceleration and grade on a second-by-second basis, as shown in Equation 1 for Light Duty Vehicles (US EPA, 2002):

$$VSP = v \times [1.1a + 9.81 \sin(\arctan(\text{grade})) + 0.132] + 0.00302v^3 \quad (1)$$

Where: v is the instantaneous speed (m/s); a the instantaneous acceleration/deceleration (m/s^2) and grade is the slope.

Since VSP accounts for changes in vehicle dynamic with high resolution time, it is suitable for the assessment of parking search process impacts on campuses. VSP values are categorized into 14 bins, and an emission factor for each bin allows estimating CO_2 and NO_x emissions for light duty gasoline (Any, Roupail, Frey, & Liu, 2013) and diesel (Coelho, Frey, Roupail, Zhai, & Pelkmans, 2009) vehicles, and light commercial diesel vehicles (Coelho et al., 2009).

Emission Costs

The emission costs considered the impacts that transportation-related emissions had on environment, economic activity and human health. These costs quantified the unequivocal estimate damage for both CO_2 and NO_x (Artem et al., 2014). After that, a ratio between local and national population densities was computed to determine the exposed of population to air pollution. To calculate unit costs of air pollution for different vehicle types, these damage costs must be combined with NO_x emission factors (Artem et al., 2014). Equation 2 provides the integrated emission costs (IEC) of each representative vehicle by VSP mode:

$$IEC_i = \sum_{j=1}^k (c_1 \mu v_j \times ef_{\text{NO}_x, j, i} + c_2 v_j \times ef_{\text{CO}_2, j, i}) \quad (2)$$

Where: IEC_i are the integrated emission costs for a representative vehicle (k is total number of vehicle classes) and VSP bin ($i = 1, \dots, 14$); c_1 and c_2 are the national damage costs of NO_x (1,957 €/ton) and CO₂ (90 €/ton), respectively (**Artem et al., 2014**); μ is the ratio between local and national population densities; v_j is the share of the vehicle type j in the car fleet and $ef_{j,i}$ the emission factor for vehicle type j for each VSP mode i (g.s⁻¹).

Total external link-specific costs per kilometer (IEC) are obtained by summing IEC_i for time spent in each VSP mode.

Safety Assessment

SSAM was developed by the Federal Highway Administration (FHWA) to estimate conflicts by safety indicators through trajectories given by microscopic traffic models as VISSIM (**F. Huang, Liu, Yu, & Wang, 2013**). Despite it has been mostly used on the evaluation of traffic conflicts at intersections, SSAM can be applied in medium-sized networks. The outputs of SSAM include the frequency, the type, the severity, and the locations of estimated conflicts. Two surrogate safety measures indicate the severity of a given conflict: 1) time to collision (TTC); and 2) post encroachment time (PET) (**Gettman, Pu, Sayed, & Shelby, 2008**).

SSAM computes three types of estimated conflicts: rear-end, lane-change and crossing conflicts. Specifically, a given interaction between two converging vehicles is tagged as a conflict when the minimum TTC and PET values drop the threshold values. The classification of conflict uses both link information and angle between converging vehicles (**Gettman et al., 2008**).

Previous studies have pointed out some concerns about SSAM, namely: capability of simulated trajectory files reflecting complex real-world driving behaviors, calibration efforts to obtain reliable safety results or unviability of SSAM to determine the probability of each estimated conflict turning into a crash (**P. Fernandes, Salamati, Roupail, & Coelho, 2017**; **Gettman et al., 2008**; **F. Huang et al., 2013**; **So, Hoffmann, Lee, Busch, & Choi, 2016**).

Notwithstanding the fact that SSAM requires an accurate calibration from traffic model, some authors have obtained reasonable relationships between estimated conflicts from SSAM and effective crashes (**Al-Ghandour, Schroeder, Williams, & Rasdorf, 2011**; **Chai & Wong, 2014**; **Dijkstra, Marchesini, Bijleveld, & Kars, 2010**; **Vasconcelos, Neto, Seco, & Silva, 2014**).

Model Calibration and Validation

This paper uses a two-stage calibration to calibrate and validate VISSIM model and adjusts threshold values in SSAM (F. Huang et al., 2013), as depicted in

Figure 2. The data collected will be separated into two groups: *i*) calibration dataset with traffic volume data; *ii*) validation dataset with vehicle dynamic data. While calibration is used to assess the impact of VISSIM driver behavior parameters on traffic flows by loop detector and set SSAM threshold values, validation focuses on testifying the effectiveness of calibrated model by comparing route-specific travel time and site crashes.

Figure 2 Calibration and Validation of VISSIM and SSAM (adapted from (F. Huang et al., 2013))

VISSIM simulation is initially calibrated to reproduce performance measures as volumes and headways observed in the field. The most significant driver behavior parameters which meaningfully impacted the distribution of headways are:

- Three parameters in the Wiedemann 74 car-following model – desired safety distance between stopped cars, and the additive and multiplicative parts of the desired safety distance;
- Three parameters in gap acceptance model – front gap, rear gap and safety distance factor;
- Two parameters in lane-change model – waiting time before diffusion and time between direction changes (PTV AG, 2011).

These parameters are adjusted and further optimized using the Simultaneous Perturbation Stochastic Approximation (SPSA) genetic algorithm (Paz, Molano, & Khan, 2014). The Geoffrey E. Havers (GEH) goodness-of-fit measure allows comparing estimated and observed traffic flows. The calibration criteria is reached after compliance with the following target: at least 85% of the all monitoring points reach GEH values lower than 4 (Dowling, Skabardonis, & Alexiadis, 2004).

The initially calibrated parameters will be run for each one-hour time interval with 10 random seed runs, as suggested elsewhere (**Winnie, Christine, & Serge P., 2014**). The vehicle trajectory files generated are processed in SSAM for identifying the estimated conflicts. Previous works (e.g. (**Gettman et al., 2008; F. Huang et al., 2013**)) make aware of many conflicts resulted in null TTC values, indicating the fact that the VISSIM may generate unrealistic simulated crashes. To overcome these limitations, several coded links must be corrected during calibration.

The second stage compares estimated travel time by route performed with those obtained in the field. A total of 10 random seed runs are generated based on this dataset. The mean absolute percent error (MAPE) is used to measure the differences between estimated and observed data (Equation 3), as follows:

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{c_e^i - c_o^i}{c_o^i} \right| \quad (3)$$

Where: n is the number of observations, c_e^i represents the estimated travel time for interval i and c_o^i is the observed travel time for interval i .

Case Study and Data Collection

The main campus of University of Aveiro (**Figure 3**), the spatial extent of this study, is near the city center of Aveiro, a European medium-sized city with 78,450 inhabitants with a population density of 397 inhabitants/km² (**Statistics of Portugal, 2017**). The campus covers an area of approximately 92 ha with 65 buildings. The teaching staff of University of Aveiro total 903 people, and there are 635 administrative staff, 14,280 registered students, and 118 researchers (**University of Aveiro, 2017a**).

Campus parking supply is approximately 1,500 spaces with a fixed price of 10€ per semester with the following distributions: P1 to P4 – 912 spaces; P5 – 42 spaces; P6 – 36 spaces; P7 – 484 spaces. These parking lots have an access system using a barrier gate operator whose opening input device is a card reader (only for university affiliates). There are additional 276 free parking spaces (P8) (**University of Aveiro, 2017b**).

The study area comprises six intersections (I1-I6), three of them serve as main accesses to the Campus Santiago (I2, I3 and I6), as shown in **Figure 3**. I5 has actuated signals and does not include any protected left-turn phasing on main directions (Northwest and Southeast). I3 is a two-lane roundabout while remaining intersections are stop- or yield-controlled intersections.

Figure 3 Location of Campus in the city of Aveiro with identification of campus area and ADT (data provided by the Municipality of Aveiro). Source [ArcGIS Maps]

The Average Daily Traffic (ADT) in the study area ranges from 1,053 vehicles at I6 south approach to 10,205 between I4 and I3. Heavy-duty vehicles represented only 1% of network-specific total traffic. Currently, the study area had some traffic congestion at the I1, I2 and I4 intersections during peak periods. This happens for the following reasons: *i*) traffic from I4 southeast and northeast approaches can only enter the campus from I2, generating high traffic volumes in the influence area of I2; *ii*) vehicles spent long times with parking search processes on campus; *iii*) no protected left-turning phasing at I1 and I4 that generates unnecessary queues and crossing conflicts.

The authors identified the following data for assessing the study area:

Site-specific data

- Posted speed limits;
- Intersection geometry;
- Crashes involving motor vehicles.

Time dependent flow data

- Intersection-specific entry and exit traffic flows;
- Origin-Destination matrices (O-D);
- Speed and acceleration-deceleration on a second-by-second basis;
- Traffic signals timing and phasing;
- Dwell time (time spent by users to enter the parking facility).

The team scouted and collected above data during the morning period (7-9 a.m.) on a typical weekday in March 2016. Manual counting was performed by volunteers at I1, I3, I4 and I6 intersection in 5-min time intervals while overhead videos recorded traffic data in the remaining intersections. More than 50 traffic monitoring points were evaluated in the study area. Based on these data, O/D matrices were defined for each intersection. Finally, both P1-P3 dwell times of and I4 traffic signals setup were gathered from videotaping.

Along with previous task, six different routes crossing the study area (**Figure 4**) were covered using GPS data-logger equipped light duty vehicle to record vehicle speed, distance travelled, and deceleration-acceleration rates in 1-second interval. Three different drivers performed those routes between 7 a.m. and 10 a.m. The sample size for vehicle dynamic data collection based on the Modified Method proposed by **Li, Zhu, Gelder, Nagle, and Tuttle (2002)**. Total data collected included 55 GPS travel runs (≈ 9 per route), which corresponded to a road coverage of 110 km.

Route 1

Route 2

Route 3

Route 4

Route 5

Route 6

Figure 4 Routes performed in vehicle dynamic data. Source [ArcGIS Maps]

Crash data involving motor vehicles were provided by Portuguese National Road Safety Authority (ANSR) for the years 2012 to 2015 (ANSR, 2017). The database covered a total of 25 crash observations in the study area: 56% related to side and rear-end collisions and 32% related to single-vehicle crashes. These crashes yielded in 24 persons with minor injuries. Concerning the location, 19 of these crashes occurred between I2 and I4 influence areas and only 2 within Campus Santiago area.

Study Area Coding

Link coding was made according to the good practices suggested herein (Fontes, Pereira, Fernandes, Bandeira, & Coelho, 2015) to account with detail the changes in vehicle dynamic (speed and acceleration-deceleration) and traffic data. Thus, both vehicular emissions and emission costs are not underestimated for a given link. The dwell time distribution was assumed to be the same for all barrier gates along campus (6 ± 3 s).

The simulation runs lasted 75 minutes (8:45-10:00 a.m.) with a 15-min warm-up period (8:45-9:00 p.m.) to load traffic onto the network. Data were then collected for the remaining 60 minutes. The campus simulation network in VISSIM is exhibited in the top left of **Figure 3**, and it has approximately 5,000 links.

Table 1 summarizes the fleet composition used in this research which considered a Portuguese car fleet (EMISIA, 2017). Heavy duty vehicles were not included in the emissions analysis since they represented less than 1% of total fleet. Also, the impact of transit buses was discarded (the campus university is only served by 1 bus during morning peak hour). Since study area is located on flat terrain, the slope was set 0.

Table 1 Car fleet composition of the study area (EMISIA, 2017).

Vehicle Type	Engine Size [L]	Split [%]
Light Duty Gasoline	1.4-1.8	33
Light Duty Gasoline	1.8-2.2	5.35
Light Duty Gasoline	>2.2	0.05
Light Duty Diesel	<1.9	40
Light Commercial Diesel	<2.5	21

Concerning the emission costs (*IEC*), the following parameters in Eq. 3 were used:

- $\mu = 3.62$ (local population density – 415 inhabitants.km⁻²; national population density – 114.5 inhabitants.km⁻²) (Statistics of Portugal, 2017);
- v_j is the share of the vehicle type ($k = 5$) which are presented in **Table 1**.

Mobility Scenarios

Building on a mobility plan process for campus area, this section describes the proposed mobility scenarios for those environmental, safety and traffic performance indicators are expected to be improved. Most of these scenarios attempt to facilitate the access to the campus parking areas:

- Baseline Scenario: Actual traffic conditions on study area where parking search routing was done using the Dynamic Traffic Assignment (**PTV AG, 2011**) since no origin-destination parking surveys were available;
- Scenario 1 (S1): Implementation of speed humps on crosswalks along campus (**Figure 5-a**);
- Scenario 2 (S2): Promoting walkability on campus by restricting traffic in the road between I3 and I5 (**Figure 5-b**);
- Scenario 3 (S3): I1 and I4 are replaced by conventional single-lane and two-lane roundabouts, respectively. In addition, vehicles can enter or exit in the campus using I4 west leg (**Figure 5-c**);
- Scenario 4 (S4): Same as previous scenario, but barrier gates are implemented in I4 west leg and they only allow entering in P1-P3 parking area (**Figure 5-d**);
- Scenario 5 (S5): Same as previous scenario, but barrier gates now allow entering or exiting P1-P3 parking and campus as well (**Figure 5-e**);
- Scenario 6 (S6): Combines scenarios 2 and 5;
- Scenario 7 (S7): Like scenario 4, but I3 is replaced by a two-lane roundabout (**Figure 5-f**). Also, vehicle must use I3 to enter in the Hospital area (this measure aims reducing conflicts between approaching south vehicles and conflicting traffic in I2).

Figure 5 Proposed mobility scenarios for the study area: a) S1; b) S2; c) S3; d) S4; e) S5; f) S7.

The analysis of emissions, conflicts and traffic performance was done both in overall network and on a link basis. Number of stops, travel time, estimated speeds and acceleration-deceleration profiles were derived from each individual vehicle (second-by-second).

RESULTS

Traffic Model Calibration and Validation

This section presents the main results regarding model calibration and validation. Using default model parameters, almost 60% of simulated conflicts had TTC values equalled 0. By inspection of simulation, it was observed that many vehicles have abrupt lane-change behavior while approaching or exiting I2. Other failed to yield to a priority rule, especially in stop-controlled intersections. Some simulated crashes were also observed while vehicles parking due to the short space between parking space and main road. Therefore, the team refined some links and changed lane change behaviors to avoid the overlapping of vehicle paths for different movements. As result, the number of simulated crashes were considerably reduced (only 13% of SSAM conflicts resulted in null TTC).

The calibration of traffic volumes in 54 loop detectors along the study area is shown in **Figure 6**. The following calibrated model parameters were obtained: desired safety distance between stopped cars – 1.4 m; additive part of the desired safety – 1.0; multiplicative part of desired safety – 1.5; front gap – 0.55s; rear gap – 0.6s; safety distance factor – 1.6; time before diffusion – 90 s; time between direction changes – 1.1 s. The comparison between estimated and observed traffic volumes dictated predicted R^2 near 97% and 94% of the loop detectors with GEH values < 4, thereby confirming a reasonable consistency between the simulated and the observed data for the study area (Dowling et al., 2004).

Figure 6 Calibration of traffic volumes.

The results for validation showed that estimated and observed travel time were only statistically significant at 5% level in the route 6 (Table 2). The comparison was performed with 10 random seed simulation runs (Winnie et al., 2014) and more than 40 floating car runs (Dowling et al., 2004). The MAPE values for the average travel time varied from 4.1%

in the route 3 to 9.1% in the route 1. The differences on the latter route occurred for two main reasons: 1) majority of demand from I4 north approach arrived during red (i.e. with poor progression); 2) vehicles stopped multiple times at the I2 west approach (campus Santiago) due to high traffic in upstream legs. Such phenomenon increased variability in travel time among trips.

As stated in the data collection section, the number of crash occurrences was low along the study area. Thus, SSAM conflicts were computed using the default TTC value of 1.5 s, as suggested by **F. Huang et al. (2013)** urban areas. The above calibrated parameters were further applied to the proposed mobility scenarios.

Table 2 Validation of travel time by route.

Route	Observed Travel Time [s]	Minimum Floating Cars	Estimated Travel Time [s]	MAPE [%]	<i>p</i> - value ¹
1	160 ± 20 ²	29	175 ± 9	9.1%	0.078
2	181 ± 15	34	197 ± 9	8.2%	0.088
3	374 ± 20	18	361 ± 14	3.5%	0.202
4	413 ± 27	18	431 ± 8	4.5%	0.215
5	314 ± 8	23	302 ± 6	4.1%	0.061
6	387 ± 29	29	414 ± 7	7.1%	0.033

Note: ¹Dataset are statistically significant if *p*-value < 0.05; ²95% Confidence Interval

Traffic performance, Energy consumption and Emissions among scenarios

Table 3 lists the average *IEC*, CO₂ per unit distance, emissions and traffic performance measures for actual campus conditions (baseline) and mobility scenarios (S1-S7).

When speed humps are used along campus (S1), no benefits were observed. Specifically, its implementation could produce more than 4% for both CO₂ per unit distance and pollutant emissions, and 3% higher travel time. The results from the S2 dictated an identical trend (*IEC*, CO₂, CO and NO_x increased by 7%, 3%, 8% and 2% on average, respectively, with the proposed scenario while idling situations and HC emissions did not vary).

S3 showed as the best solution for the study area. It yielded an average reduction in *IEC*, CO, NO_x and HC emissions of 9%, and recorded the lowest number of vehicle stops, with 36%. With exception of the travel time, the difference in analysis measures between baseline and S3 was statistically significant at the 5% significance level (*p*-value < 0.05). The satisfactory performance of S3 occurred for two main reasons: 1) vehicles did not perform complete stops at new I1 and I4 roundabouts (especially those from minor roads); 2) vehicles from I4 South and East approaches need not use I2 and I3 to access to the campus and parking areas.

S4 also improved all outputs compared to the baseline scenario. The average decrease in emissions ranged from 5% to 7% between CO₂ and NO_x. Even though vehicles must be stopping to the barrier gates in P1-P3 parking (**Figure 5-e**), S4 achieved substantial idling and travel time reductions motivated by the changing in both I1 and I4 layouts.

S5 was the best next scenario to be implemented in the campus Santiago. It reduced costs and CO₂ per unit distance in 8% and 5%, respectively, and approximately 31% fewer stop-

and-go situations. However, S5 did not result in considerable travel time savings when compared to the existing conditions, largely, explained by the fact that vehicles are obligated to come to a complete stop at barrier gates near I4.

Regarding S6, the site-specific costs, traffic performance, emissions and energy outcomes were improved but its benefits were less pronounced than those recorded in previous scenarios. This happened because vehicles from I3 North approach must use barrier gates near I4 to enter the campus.

Although reductions in stop-and-go were likely to be achieved for S7, this solution would not provide any global competitive advantage over the remaining mobility scenarios. There were increases in CO emissions and travel time of 2% and 4% on average, respectively, compared with that of the existing conditions.

Table 3 External costs, traffic performance, energy and pollutant emissions by scenario (average with standard deviation).

Scenario	Costs	Traffic Performance		Energy	Pollutant Emissions			
	IEC [€/km]	Travel Time [s/veh]	Total Stops	CO ₂ [g/km]	CO ₂ [kg]	CO [g]	NO _x [g]	HC [g]
Baseline	8.3	254	1,426	230	656	826	1,942	35
	(0.4)	(7)	(49)	(3)	(26)	(34)	(81)	(2)
S1	8.7	261	1,435	239	679	859	2,020	36
	(0.3)	(6)	(53)	(3)	(27)	(35)	(86)	(1)
S2	8.9	258	1,426	236	676	896	1,986	35
	(0.7)	(7)	(40)	(9)	(31)	(105)	(95)	(1)
S3	7.6	245	919	215	604	760	1,773	32
	(0.2)	(6)	(24)	(3)	(95)	(10)	(30)	(1)
S4	7.8	253	981	216	620	780	1,814	33
	(0.4)	(6)	(40)	(1)	(20)	(25)	(62)	(1)
S5	7.7	247	982	219	615	774	1,787	32
	(0.3)	(5)	(40)	(5)	(24)	(27)	(62)	(1)
S6	8.0	250	1,041	220	623	780	1,808	33
	(0.3)	(5)	(39)	(1)	(22)	(30)	(71)	(1)
S7	8.1	263	1,079	221	649	840	1,934	34
	(0.2)	(7)	(31)	(3)	(25)	(71)	(114)	(1)

Legend: Average values using 10 random seed runs; Shadow cells indicate that the difference between mobility and baseline scenario output measure was not statistically significant (p -value < 0.05)

To complement this analysis, the hotspot costs and CO₂ per unit distance locations on the study area were examined, as exhibited in **Figure 7**. It was observed that the links among

I1, I2 and I4 recorded the highest costs and CO₂ values in the baseline scenario (**Figure 7 a-b**). Specifically, these areas yielded 142% more *IEC* and 38% more CO₂ emissions than the average values (*IEC* – 8.3 €.km⁻¹ and CO₂ – 230 g.km⁻¹) of the Campus. Albeit lengthy, the main road along campus had moderate *IEC* (<10 €.km⁻¹) and CO₂ (<175 g.km⁻¹) values. S3 resulted in fewer links with red colors at the influence areas of I2 and I4 (**Figure 7 c-d**), thereby confirming its benefits on campus boundaries. However, increases of 40% and 20% in *IEC* and CO₂ per kilometer, respectively, can be expected on road near P1-P3 and P8 when compared to the baseline scenario.

Figure 7 Overview link costs and CO₂ in the campus area: a) IEC – Baseline; b) CO₂ – Baseline; c) IEC – S3; d) CO₂ – S3.

Traffic conflicts among scenarios

This section compares traffic conflicts and road safety measures among scenarios. SSAM outputs are summarized in **Table 4**. Several conclusions about the impact of the proposed mobility scenarios can be stressed:

- i) Baseline scenario was the worst safety option according to the number of conflicts criterion;
- ii) As suspected, the total number of conflicts significantly decreased after I1 and I4 being replaced by roundabouts (more than 26% in S3 and S5);
- iii) S3 was found to be the best option according to both the number of rear-end conflicts (-36% compared to baseline) and severity of conflicts ($>TTC$ and PET values);
- iv) S6 was very effective in reducing the number of lane change conflicts (~40% less compared to the baseline) mostly due to the fact vehicles did not change from left to right lane at I2 north approach to enter the campus;
- v) For every scenario, the difference in the number of crossing conflicts, TTC and PET values was not statistically significant (p -value > 0.05).

Figure 8 shows conflicts for the baseline, and S3 and S5 (best scenarios for the study area). The concentration of traffic conflicts in the baseline scenario was found at the most heavily congested I1 and I2 entries and near P1-P3 parking area (**Figure 8** Figure 7a). Also, the signalized intersection (I4) also had a predominance of rear-end conflicts (yellow triangles), especially in North and South main approaches. Both S3 and S5 visibly reduced the number of conflicts at I4 influence area and I2 south approach (vehicles that came from South study area no longer use I2 to enter to campus), as illustrated in **Figure 8** Figure 7b-c. Yet, SSAM graphical representation showed that additional crossing conflicts occurred in the intersection between new entrance and campus main road. This phenomenon may represent future operational and safety issues if more drivers choose to use this new entrance to the campus area. This aspect will be addressed in the next section.

Table 4 Traffic conflicts, TTC and PET values by scenario (average with standard deviation).

Scenario	Conflict Type				Safety Measure	
	Crossing	Lane Change	Rear End	Total	TTC [s]	PET [s]
Baseline	7	45	123	175	1.26	1.92
	(6)	(6)	(10)	(23)	(0.02)	(0.09)
S1	6	37	127	169	1.27	1.92
	(4)	(6)	(18)	(20)	(0.02)	(0.09)
S2	8	42	136	185	1.25	1.88
	(3)	(6)	(17)	(19)	(0.02)	(0.06)

S3	6	33	79	118	1.28	1.95
	(3)	(8)	(18)	(24)	(0.05)	(0.12)
S4	6	35	86	127	1.26	1.93
	(2)	(4)	(21)	(21)	(0.03)	(0.09)
S5	4	31	95	130	1.25	1.94
	(2)	(8)	(17)	(19)	(0.03)	(0.08)
S6	7	28	108	143	1.26	1.94
	(4)	(11)	(9)	(16)	(0.04)	(0.15)
S7	2	38	110	150	1.26	1.94
	(1)	(7)	(19)	(14)	(0.04)	(0.05)

Figure 8 Hotspot conflicts location: a) Baseline Scenario; b) S3; c) S5.

Sensitivity Analysis

Considering the foregoing discussion, the baseline, S1 and S3 scenarios were compared under different traffic volumes at the new campus entrance from I4 west leg. Currently, the traffic demand on the subject approach is approximately 60 vph. Thus, the effects of uniform traffic growth were explored by applying 50-vph increment on the subject approach up to the saturation of the corresponding scenario (vehicles no longer enter in the study domain).

For purpose of the analysis, the increase in traffic volumes will be made from I4 South and West approaches where most of the drivers will use to enter the campus.

Figure 9 displays the effects of varying the traffic demand at the above scenarios on travel time, *IEC*, CO₂ and NO_x emissions, and number of conflicts. Main results are described as follows:

- i)* Baseline scenario was very sensitive to the increase in traffic demand as a traffic performance point of view. On average, the relative travel time difference in relation to S3 increased as traffic demand increased (from 4% to 16% in 110 vph and 360 vph demand scenarios, respectively);
- ii)* S3 is the most robust mobility scenario, regardless of traffic demand scenario. Also, it can receive additional traffic (12% and 28%, respectively, compared to baseline and S5) before it becomes congested (~460 vph);
- iii)* Albeit efficient, S5 reached saturation before baseline scenario or S3 (~360 vph on the subject approach). This was due to the fact that vehicles complete stops at the barrier gates, causing congestion in I4 roundabout. Noted that the distance from those gates and I4 exit lane is considerably short;
- iv)* S3 and S5 showed as good options up to vehicle demands of 260 vph. Both scenarios decreased emissions in 1% and 4% for CO₂ and NO_x, respectively and costs up to 2% compared with that of the existing conditions;
- v)* Under high demand scenarios (>310 vph), S5 performed poorly according the emissions and costs criteria. For instance, if demand on subject approach was 360 vph, then S5 would increase 21%, 14% and 30% of CO₂, NO_x and *IEC*, respectively, when compared to the baseline scenario.

a)

b)

c)

d)

e)

Figure 9 Outputs trends with variations in traffic demand: a) travel time; b) *IEC*; c) CO₂; d) NO_x; e) Number of Conflicts.

Overall, the adoption of a given mobility measure may result in lower benefits than initially expected. Rather than selecting the best scenario, this section stressed the importance of assessing impacts (before their implementation) based on traffic forecasting. Consequently, depending on the choice of drivers, some decisions must be deeper studied and carefully taken to avoid negative impacts on campus performance as a whole.

CONCLUSIONS

This research examined the impact of different mobility scenarios on a campus-specific traffic performance, conflicts, emission-related costs, and global and local pollutants. The paper also identified the hotspots of their impacts along the study area.

Field data were collected from a University campus in the city of Aveiro, Portugal. Some of the proposed scenarios were intended to facilitate the access to campus parking areas as well as to improve the quality of University staff. Each scenario was coded and implemented using a calibrated and validated modeling platform of traffic (VISSIM) which was paired to an emissions (VSP) and safety (SSAM) models using the speed trajectories from the traffic model.

The methodology applied showed that some of the mobility measures in a University campus were feasible. The main research conclusions were as follows:

- Assuming the actual conditions, the implementation of speed humps (crosswalks) and walkability (traffic restriction on one access road) slight increased both the amounts of emissions and the occurrence of traffic conflicts;
- Creating a fast access to the University campus by using a two-lane roundabout that replaced the existing signalized intersection showed as the best option (-9% emission costs, CO, NO_x and HC, 36% less idling situations and 24% fewer traffic conflicts) to the study area;
- The use of barrier gates on a new campus access and one of the existing parking facilities also provided satisfactory results (decrease in emissions ranged from 5% to 7% between CO₂ and NO_x; traffic conflicts decrease in more than 25%);
- The proposed scenarios reduced conflicts at the intersections that allows entering/leaving the campus, but resulted in additional conflicts at the main road within campus;
- The overall performance of these scenarios markedly decreased when the traffic demand at the new access increased. This was particularly true when barrier gates were adopted in a new access to campus with a traffic demand higher than 310 vph.

Despite the moderate improvements on campus-specific outcomes, this work filled a gap in the current state-of-art, and contributes with the following aspects:

- To identify both the positive and the negative impacts concerning the implementation of specific mobility measures on University campus environments;
- To provide information about the traffic-related impacts with high-level of detail (i.e., link-by-link basis);

- To integrate different criteria (environmental, economic, energy, safety and mobility) to account campus-specific needs and vulnerabilities in the context of road transportation;
- To include a sensitivity analysis of future traffic demand scenarios to explore non-expected operational issues that carried out from changes in campus mobility.

Future work will be mostly focused on the assessment and comparison of each scenario during peak hours. Also, some field work will be performed in transit buses by testing changes in buses routes along the campus before changing campus road network. Lastly, the modeling of cyclists will be incorporated on the modeling platform.

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