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Traffic restriction policies in an urban avenue: A methodological overview for a trade-off analysis of traffic and emission impacts using microsimulation

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ABSTRACT

Urban traffic emissions have been increasing in recent years. To reverse that trend, restrictive traffic measures can be implemented to complement national policies. We have proposed a methodology to assess the impact of three restrictive traffic measures in an urban arterial by using a microsimulation model of traffic and emissions integrated platform. The analysis is extended to some alternative roads and to the overall network area. Traffic restriction measures provided average reductions of 45%, 47%, 35%, and 47% for CO_2, CO, NO_X, and HC, respectively, due to traffic being diverted to other roads. Nevertheless, increases of 91%, 99%, 55%, and 121% in CO_2, CO, NO_X, and HC, respectively, can be expected on alternative roads.

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Emissions; integrated platform; microscopic simulation; traffic restriction measures

1. Introduction and objectives

In Europe, emissions of greenhouse gases (GHGs) from the transportation sector increased by 19% between 1990 and 2011 and account for about 20% of total emissions (EEA, 2013). Some tools have been developed to quantify the impacts of current urban patterns of transportation on emission impacts and air quality (Bandeira, Coelho, Sá, Tavares, & Borrego, 2011; Barros, Fontes, Silva, & Manso, 2013; Coelho, Farias, & Rouphail, 2009). In the last decade, several measures were developed to improve air quality in cities. These measures can either be from the vehicle side or the road side. Focusing on road-side measures, optimization tools for traffic signal timing are used to reduce fuel consumption and vehicular emissions as well as traffic delays and stops (Stevanovic, Stevanovic, Zhang, & Batterman, 2009; Zhang, Chen, Zhang, Song, & Yu, 2009). In addition to these, traffic restriction measures represent effective yet unpopular tools to both reduce vehicular congestion and improve air quality within the city centers. Nonetheless, a measurable improvement in air quality is needed to demonstrate the effectiveness of those measures (Castro & Delos Reyes, 2010; Invernizzi et al., 2011).

The use of microsimulation models has recently become more commonplace in the study of transportation problems regarding environmental implications of policy measures. Specifically, these models allow exporting the vehicle position and vehicle dynamics (acceleration/deceleration and speed) second-by-second, which provides accurate emission estimation. Note that their simulation outputs as speed and acceleration/deceleration can be employed in instantaneous emissions models. These emission models can be used to assess the environmental impacts of different traffic management strategies applied to the road network traffic, such as, route diversion, lanes management, variable speed limits, or traffic signal coordination (Aziz & Ukkusuri, 2011).

The methodology usually followed in previous works was to integrate a traffic model with an emission model. Table 1 lists the most relevant studies on the effects of traffic restriction measures on vehicular emissions and traffic performance using a simulation approach. Moreover, it indicates the spatial and temporal extents, and also the environmental and performance goals proposed in each work. These studies can be divided into two main groups. In the first group (Chen & Yu, 2007; Int Panis et al., 2011; Nesamani, Chu, & Recker, 2010; Qu, Rillet, Zhang, & Zietsman, 2003; Torné, Rosas, & Soriguera, 2011), only one traffic restriction measure is assessed; and in the second group (Lee et al., 2012; Mahmod, Van Arem, Pueboobpaphan, & Igamberdiev, 2010), comparisons of several traffic restriction measures for the same location are conducted.

Many studies have proven to be inconclusive about the environmental benefits of speed limit reductions (Qu et al., 2003, Torné et al., 2011) and bus-only lane implementation (Chen & Yu, 2007). Madireddy et al. (2011) concluded that the reduction of speed limits from 50 km/h to 30 km/h in residential areas provided a 25% reduction of carbon monoxide (CO) and nitrogen oxide (NO_X) emissions.

Mahmod et al. (2010) suggested that reducing traffic demand and heavy duty vehicles led to a decrease of CO, NO_X, and PM_{10} emissions by more than 20%. Lee et al. (2012) found that the fleet replacement of Drayage trucks by lower-emission trucks on an urban freight corridor yielded a significant

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Table 1. **Most relevant research on the impact of traffic restriction strategies in terms of emissions and traffic performance measures using simulation models.**

	Reference	Spatial extent	Study location	Temporal extent	Environmental performance measures goals	Traffic restriction measures	Assessment of alternative roads
1	Qu et al., 2003	Freeway section	Houston, T	6–7 a.m. and 10–11 a.m.	CO, NO_X, HC	Speed limit reduction	No
2	Chen and Yu, 2007	Urban road network (∼5.7 km^2)	Beijing, China	7–9 a.m.	CO, NO_X, HC	Bus-only lane	No
3	Nesamani et al., 2010	Only freeway network (∼207 km^2)	Orange County, CA	One hour during morning peak hour (not specified)	CO_2, CO, HC, NO_X, speed, VMT, VHT	Hybrid-high occupancy lane use	No
4	Madireddy et al., 2011	Urban arterial road	Antwerp, Belgium	One hour during morning peak hour (not specified)	CO_2, NO_X	Speed limit reduction	No
5	Int Panis et al., 2011	Urban arterial roads	Mol, Belgium and Barcelona, Spain	Not available	CO_2,CO, NO_X, HC, PM	Speed limit reduction	No
6	Torné et al., 2011	Single metropolitan highway	Barcelona, Spain	7:10–11:20 a.m., 5:40–7:15 p.m., 10–12 p.m. and 0–6 a.m. and rest of the day	CO_2, NO_X, and PM_{10}, travel times	Speed limit reduction	No
7	Mahmod et al., 2010	Single intersection	Rotterdam, the Netherlands	7–8 a.m.	CO_2, NO_X, and PM_{10}, speed, delay, vehicle stops	Demand control reduction, removing heavy duty vehicles, speed limit reduction, and adaptive cruise control	No
8	Lee et al., (201	Freeway and arterial network (∼4 k	San Pedro Bay Ports, CA	7 a.m.–7 p.m.	CO, NO_X, HC, PM, speed, VMT, VHT	Removing heavy-duty trucks, bulk and break-bulk trucks	No
9	This article	Urban road network(∼4 km^2)	Lisbon, Portugal	7–8 a.m. and 5–6 p.m.	CO_2, CO, HC, NO_X, speed, delay, vehicle stops	Bus-only lane, closing all traffic, dropping one lane	Yes

VMT: Vehicle Miles Traveled; VHT: Vehicle Hours Traveled.

reduction in NO_X and particulate matter (PM) emissions in 48% and 55%, respectively, between 2012 and 2005. Nesamani et al. (2010) showed that hybrid-high occupancy lanes were less effective with regard to flow-mixed lanes when hybrids' percentage exceeded 19%.

From the above-mentioned references some observations can be made. First, the majority of researchers used different traffic simulation tools to analyze the effect of traffic restriction measures in limited study areas (Int Panis et al. 2011; Madireddy et al., 2011; Mahmod et al., 2010; Qu et al., 2003). Second, some studies with a significant spatial extent analysis (Chen & Yu, 2007; Lee et al., 2012; Nesamani et al., 2010) were focused on one time analysis period. Third, the effects of traffic restriction measures in other individual road networks were not taken into account.

Thus, a more extensive analysis that combines both emissions and traffic performance assessment is needed. The analysis should include different network areas within the case study at different periods of the day in order to reflect reality and improve the knowledge to develop further traffic restriction strategies. In this study (see Table 1), we seek to contribute to the literature by providing a more accurate assessment of traffic restriction strategies in urban areas. As such, we developed a methodology to evaluate multiple traffic restrictions using a microsimulation approach.

This paper intends to focus on the following research questions:

- How can different traffic restriction measures affect emissions and traffic performance on multiple roads in the study area?
- How do vehicular emissions vary during morning and evening peak hours for different traffic restriction measures?

Section 2 describes the methodology developed in this study. Information regarding simulation steps, data sources used in its development, and an application in a real-world case study are provided in detail. Next, analysis results are presented and discussed in section 3, followed by the main conclusions in Section 4.

2. Material and methods

The main goal of the proposed methodology is to develop a microscopic simulation platform of traffic and emissions. This platform allows direct evaluation of the impact of traffic restriction measures on the atmospheric environment in urban areas. A summary of the modeling framework is depicted in Figure 1. The models (see section 2.1), as well as data collection (see section 2.2) and the methodology for calibration and validation (see section 2.3) are described briefly herein. Finally, a real-world case study (see section 2.4) with traffic restriction measures is presented (see section 2.5).

2.1 Platform of microscopic traffic and emission modeling

To evaluate traffic restriction measures at the urban level, we defined a microscopic simulation platform of traffic and emissions. This approach attempts to represent traffic and emissions on a second-by-second basis.

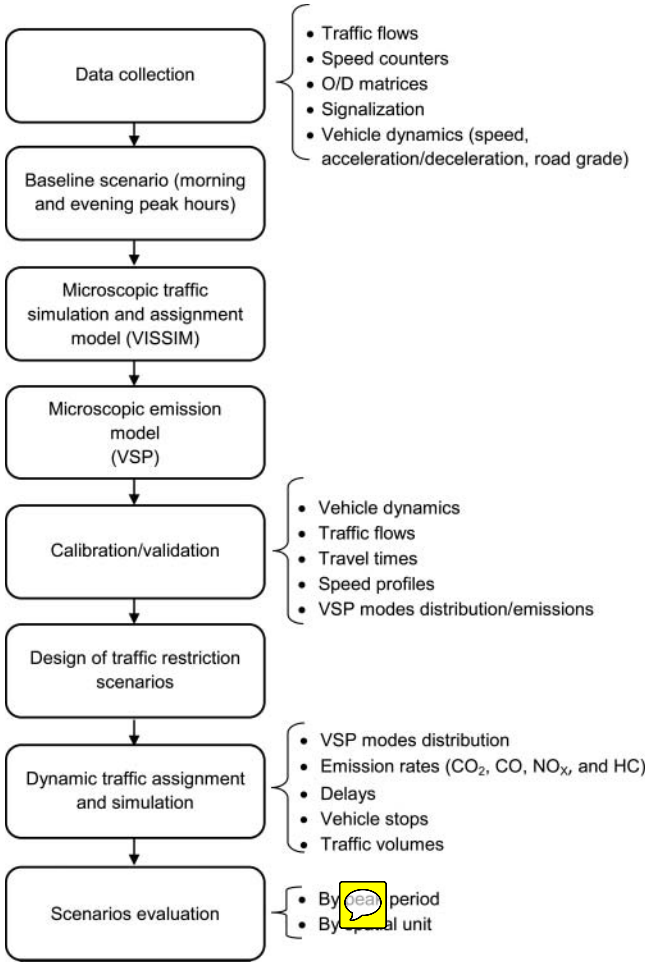

Figure 1. Methodological simulation framework.

A microscopic traffic model describes the behavior of individual drivers as they react to their perceived surroundings. It also offers detailed vehicle operation and instantaneous speed and acceleration of vehicles required by the microscopic emission models in order to evaluate the environmental impact of transportation policies such as traffic restriction measures. We used the VISSIM 5.30 microscopic traffic model to simulate traffic conditions (PTV, 2011). VISSIM was selected because of the possibility to define and use different road-user behavior parameters and submodels (car-following, gap-acceptance, lane change) for different vehicle types and traffic controls modeling (PTV, 2011). A good deal of literature has documented the effective use of VISSIM in analyzing some traffic restriction and management strategies in real-world case studies (Chen & Yu, 2007; Fontes et al., 2[illegible]; Mahmod et al., 2010).

The emission calculation is made by using the "Vehicle Specific Power" (VSP) methodology. This model is based on vehicle speed, acceleration/deceleration, and road grade and has proven to be very useful in estimating instantaneous emissions for gasoline and diesel vehicles (Coelho, Frey, Rouphail, Zhai, & Pelkmans, 2009; Frey, Zhang, & Rouphail, 2008) as well as transit buses (Zhai, Frey, & Rouphail, 2008). Several motivations have supported the use of VSP methodology in this research: (a) VSP can be applied for both U.S. and European car fleets because it includes a wide range of engine displacement values; (b) VSP methodology was shown to produce accurate trip fuel consumption estimates for diesel transit buses (Frey, Rouphail, Zhai, Farias, & Gonçalves, 2007); and (c) recent research (Kolak, Feyzioglu, Birbil, Noyan, & Yalcindag, 2013) concluded that the VSP-based emission model not only has a better estimation of vehicle emissions than a speed-based emission model but also is capable of reflecting the emission changes under different operating modes.

The VSP values are categorized in 14 modes and an emission factor for each mode is used to estimate carbon dioxide (CO_2), CO, NO_X, and hydrocarbons (HC) emissions from Light Duty Diesel Vehicles (LDDV<1.8 L) and Light Duty Gasoline Vehicles (LDGV<3.5L). Equation 1 provides the VSP calculation for Light Duty Vehicles (LDV) (U.S. EPA, 2002):

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

where:

v = Instantaneous speed (m/s);
a = Instantaneous acceleration or deceleration (m/s^2);
$grade$ = Road grade (decimal fraction).

These terms represent the engine power required in terms of kinetic energy, road grade, friction, and aerodynamic drag (Frey et al., 2008). VSP values are usually grouped in combinations of 1 kW/ton from −50 to +50. Then, these values are categorized in modes so that each mode generates an average emission rate. Concerning transit buses, VSP is estimated using typical coefficient values and expressed by Equation (2) (Zhai et al., 2008):

$$VSP = v\times[a + 9.81\times\sin(grade) + 0.092] + 0.00021\times v^3 \tag{2}$$

where:

v = Instantaneous speed (m/s);
a = Instantaneous acceleration or deceleration (m/s^2);
$grade$ = Road grade (decimal fraction).

In this case, VSP combinations are grouped in eight modes that correspond to values ranging from −30 to 30 kW/ton (Zhai et al., 2008).

Table 2 presents the average modal emission rates for LDGV, LDDV, and transit buses based on VSP bins. After the VSP value is calculated, the VSP mode is determined by the

Table 2. Mean values for CO_2, CO, NOx, and HC emission rates (g/s) for VSP modes for Light Duty Diesel Vehicles (LDDV), Light Duty Gasoline Vehicles (LDGV), and transit buses.

			Average modal emission rates			
Vehicle Type	Definition (kW/ton)	VSP Mode	CO_2 (g/s)	CO (g/s)	NO_X (g/s)	HC (mg/s)
Light Duty Gasoline Vehicles (LDDV) (USEPA 2002)	$VSP^1 < -2$	1	1.7	0.008	0.0009	0.40
	$-2 \le VSP < 0$	2	1.5	0.004	0.0006	0.30
	$0 \le VSP < 1$	3	1.1	0.003	0.0003	0.40
	$1 \le VSP < 4$	4	2.2	0.008	0.0012	0.40
	$4 \le VSP < 7$	5	2.9	0.011	0.0017	0.50
	$7 \le VSP < 10$	6	3.5	0.017	0.0024	0.70
	$10 \le VSP < 13$	7	4.1	0.020	0.0031	0.80
	$13 \le VSP < 16$	8	4.6	0.029	0.0042	1.00
	$16 \le VSP < 19$	9	5.2	0.036	0.0051	1.10
	$19 \le VSP < 23$	10	5.6	0.055	0.0059	1.40
	$23 \le VSP < 28$	11	6.5	0.114	0.0076	2.10
	$28 \le VSP < 33$	12	7.6	0.208	0.0121	3.40
	$33 \le VSP < 39$	13	9.0	0.442	0.0155	4.90
	$VSP \ge 39$	14	10.1	0.882	0.0179	10.90
Light Duty Diesel Vehicles (LDGV) (USEPA 2002)	$VSP^1 < -2$	1	0.2	0.00003	0.0013	1.29
	$-2 \le VSP < 0$	2	0.6	0.00007	0.0026	2.62
	$0 \le VSP < 1$	3	0.7	0.00014	0.0034	3.38
	$1 \le VSP < 4$	4	1.5	0.00025	0.0061	6.05
	$4 \le VSP < 7$	5	2.3	0.00029	0.0094	9.36
	$7 \le VSP < 10$	6	3.3	0.00069	0.0125	12.53
	$10 \le VSP < 13$	7	4.2	0.00058	0.0155	15.48
	$13 \le VSP < 16$	8	4.9	0.00064	0.0178	17.82
	$16 \le VSP < 19$	9	5.6	0.00061	0.0213	21.32
	$19 \le VSP < 23$	10	6.3	0.00101	0.0325	32.53
	$23 \le VSP < 28$	11	7.4	0.00115	0.0558	55.75
	$28 \le VSP < 33$	12	8.4	0.00096	0.0743	74.35
	$33 \le VSP < 39$	13	9.4	0.00077	0.1042	104.16
	$VSP \ge 39$	14	10.5	0.00073	0.1459	145.94
Transit buses (Zhai et al. 2008)	$VSP^2 < 0$	1	2.4	0.009	0.04	1.23
	$0 \le VSP < 2$	2	7.8	0.036	0.13	1.70
	$2 \le VSP < 4$	3	12.5	0.045	0.18	1.75
	$4 \le VSP < 6$	4	17.1	0.072	0.22	1.84
	$6 \le VSP < 8$	5	21.2	0.085	0.24	1.94
	$8 \le VSP < 10$	6	24.8	0.091	0.26	2.05
	$10 \le VSP < 13$	7	27.6	0.084	0.28	2.08
	$VSP \ge 13$	8	29.5	0.062	0.31	2.15

[1] As computed by Equation (1)
[2] As computed by Equation (2)

VSP range. The corresponding modal emission rates for CO_2, CO, NO_X, and HC are then obtained.

2.2 Data collection

Several inputs are required to the integrate platform of microsimulation. For this process, the following data collection must be provided:

1) Traffic counts by vehicle class;
2) Speed counts;
3) Time-dependent O/D matrices;
4) Cycle length and green times for traffic lights;
5) Vehicle dynamics (speed, acceleration/deceleration, and road grade).

This data collection was performed on several roads and took into account several factors: network and route types, traffic demand, driver scheduling, and selected vehicles classes. Note that all data collection demand was collected hourly, with the exception of vehicle dynamics.

2.3 Model calibration and validation

Model calibration and validation are very crucial processes in traffic simulation analyses. Before calibrating, we must define which performance measures to use as an index of comparison between simulation results and collected data. In this study, we selected travel times and speed as the main calibration data for urban case studies because these measures reflect the driving behavior parameters and the level of service (Dowling, Skabadonis, & Alexiadis, 2004).

In this paper, we present a calibration and validation methodology that can be performed in five steps. The first three steps are related to the calibration of the traffic model, while the following steps are focused on validation of the simulated data.

First we calibrate both the desired speed and acceleration distributions, then the driver behavior parameters of the traffic model used in order to assess their effect on travel times and speed. These can be divided into car-following parameters (average standstill distance, additive and multiple part of safety distance), lane-change parameters, and simulation resolution. The calibration strategy recommended by Dowling et al. (2004) was followed. This included the following: first calibrate capacity parameters, then route choice parameters, and finally the overall model performance. In each step, all parameters that affect the simulation on a global basis first and then those that have an impact on a local basis (i.e., link-specific parameters) should be adjusted.

In the third step, a preliminary number of runs are selected using traffic volumes, travel times, average speed, and acceleration measures, separately. The methodology suggested by Hale (1997) is followed.

To validate the results of the traffic simulation model, we carried out a comparison between traffic counts, travel times, speeds, and acceleration with observed data for a preliminary number of runs selected previously. The Geoffrey E. Havers (GEH) statistic test (Dowling et al., 2004) and the Root Mean Square Error (RMSE) (FHWA Travel Mode Improvement Program, 2010) are used to compare means and overall "goodness of fit," respectively.

The fifth step is focused on a comparison between observed and estimated VSP mode distributions and respective CO_2, CO, NO_X, and HC emissions. Because the number of data sets (number of seconds of the route) is roughly higher than 30 (Everitt & Hothorn, 2006) the two-sample Kolmogorov-Smirnov test (K-S test) for a 95% confidence level is appropriate to assess if the probability distributions of two samples are different.

2.4 Selected case study

To evaluate the efficacy of an integrated platform on traffic restriction measures assessment, we selected an urban arterial in Lisbon (Portugal). The case study network is comprised of a wide central road, two service roads and four signalized intersections. Due to its central location, Liberdade Avenue (LA) has a high traffic demand that can reach 1,600 vehicles/hour on its central roads during evening peak hours. Thus, this road network is an interesting case for studying traffic restriction measures to evaluate their effects on emission and road traffic performance parameters. Figure 2 shows the map of city study area with the LA and alternative roads 1 (AR1) and 2 (AR2) identified. These roads allowing traffic in both directions are the only ones that provide similar trips to LA. Overall speed limit in the study area is 50 km/h.

In this domain, the data required for the integrated platform of traffic and emissions presented in section 2.3 were collected. Network-wide traffic demands (see Figure 2), and traffic signal and average speed counters were obtained from the Traffic and Road Safety Department of Lisbon Municipality. These local O/D matrices (see Figure 2) have resulted from surveys that have been carried out in different areas of Lisbon's central area during the morning and evening peak periods. The above O/D matrices included both LDV and heavy duty vehicles. Concerning traffic counts data, they included the following vehicles types: Light Duty Vehicles, Heavy Duty Vehicles, and transit buses. Because Heavy Duty Vehicles represented less than 1% of traffic composition, we excluded them from this evaluation. After that, we adjusted global O/D demands (between centroids) to match traffic flows data in 60 min intervals on the road loop detectors with available data. We performed this procedure on both morning peak and evening peak periods. For intersections without traffic data, we assumed turning flow fractions similar to those of neighboring locations. Regarding urban traffic buses, their schedules, headways, and bus stop locations were calibrated using the real values of the Lisbon Bus Company. Data were collected in four routes across LA in order to cover all trips that can be performed on the central and service roads. For each route, we performed more than 30 runs.

The emission model was used to estimate CO_2, CO, NO_X, and HC emissions for LDV and transit buses. In order to reflect the actual Portuguese fleet as closely as possible, the considered emissions rates are based on 57.5% LDGV and 42.5% LDDV with engine size smaller than 3.5 L (ACAP, 2012). We assumed that the effect of road grade was not relevant (*grade* = 0). To support this, we compared CO_2, CO, NO_X, and HC emissions,

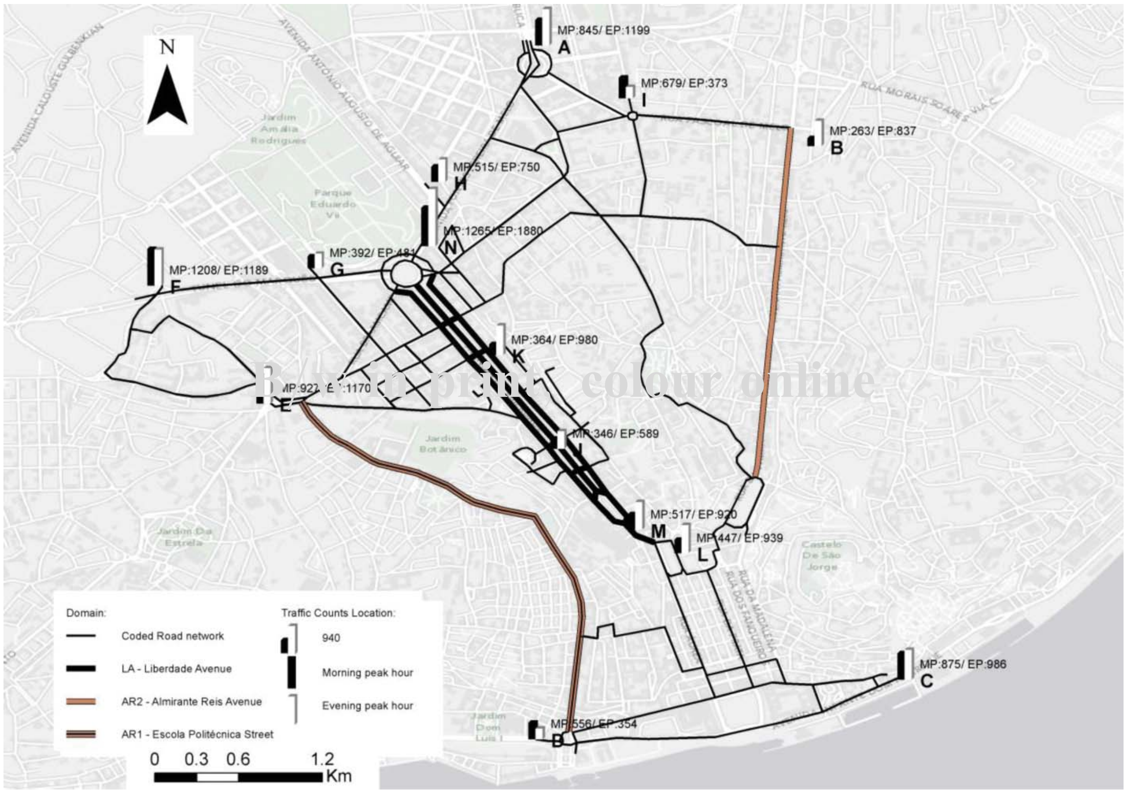

Figure 2. Study domain.

for each route performed, considering (a) the real road grade every second and (b) road grade value of 0. For all pollutants, we found that the differences between the two cases were lower than 3%. In addition, we also recorded traffic performance parameters related to number of vehicles, vehicle stops, and delays.

During weekdays, traffic counts suggest that morning and evening peak hours occur between 7–10 a.m. and 4–7 p.m. Thus, the periods between 7–8 a.m. and 5–6 p.m. were chosen to simulate the morning and evening peak hours, respectively. It should be mentioned that traffic demand on LA is higher in northbound lanes during the evening peak period whereas significant differences between northbound and southbound lanes during the morning peak period were not observed.

2.5 Scenarios

Calibration and validation were done for the baseline scenario. This scenario corresponds to the reference situation on the LA corridor in which traffic flow is assigned to routes by using Dynamic Traffic Assignment (DTA) (PTV, 2011). In order to assess emissions and traffic performance of several traffic restrictions, three traffic scenarios to be implemented on the LA corridor are evaluated (Figure 3):

- Baseline scenario: This corresponds to the actual situation of LA in which traffic flow is assigned to routes on the basis of a traditional user equilibrium model (Figure 3.a);
- Scenario 1: Removal of left lane on the central road of LA (southeast to northwest direction) with 750 meters of length. Additionally, service road capacity is reduced to one circulating lane with 3.5 meters of width (Figure 3.b);
- Scenario 2: Implementation of a bus-only lane in the central road of LA with 800 meters of length (Figure 3.c);
- Scenario 3: Similar to scenario 2, but the central road of LA is closed to traffic (Figure 3.d).

In these scenarios, we also assumed that traffic is diverted to the alternative roads by applying DTA in the VISSIM model, considering the travel time as the only factor impacting routes choice (PTV, 2011). This was done due to the fact that no information about driver's route choice factors in the study domain could be found. Because bus stops were in the same location for both scenarios 1 and 2, we considered that transit buses had the same path from origin to destination as in the baseline scenario. There was an exception in scenario 3 in which the bus stops located on the central road were re-placing at the lateral roads.

The emissions and traffic performance of each traffic restriction scenario are evaluated in terms of: (a) LA; (b) AR1 and AR2; and (c) overall network (ON). Traffic flows, number of stops, and estimated acceleration and deceleration profiles are derived from the vehicle dynamics data (second-by-second), while delays are obtained from the node evaluation (PTV, 2011).

3. Results and discussion

In this section we present and discuss the main results obtained from traffic and emissions models calibration and validation (see section 3.1). After that, environmental and performance

Figure 3. Schematic of traffic restriction scenarios: (a) baseline scenario; (b) scenario 1; (b) scenario 2; (d) scenario 3.

Table 3. Observed and simulated travel time and mean speed (VISSIM default parameters) during the morning peak hour.

Parameter	Route	Sample size (N_{MIN})	Observed (95%CI)	Simulated (95%CI)	*GEH* statistic
Travel time (seconds)	1	10 (3)	311.6 (15.9)	276.7 (9.9)	2.1
	2	14 (4)	191.2 (11.0)	171.4 (6.6)	1.5
	3	10 (6)	410.7 (7.8)	380.2 (18.3)	1.5
	4	12 (9)	288.3 (12.4)	262.0 (12.1)	1.6
Speed (km/h)	1	10 (3)	18.1 (0.8)	20.1 (0.7)	2.0
	2	14 (4)	25.8 (0.1)	28.5 (0.6)	2.3
	3	10 (6)	15.0 (0.5)	17.2 (1.0)	1.5
	4	12 (9)	19.8 (0.8)	22.3 (1.3)	1.9

impacts from traffic restriction measures during the morning

Table 4. Observed and simulated traffic flows (vph) for morning and evening peak hours.

Period	Counter	Observed flow	Simulated flow (95%CI)	RMSE (%)	*GEH* statistic
Morning peak hour	A	845	842.3 (5.3)	1.9%	0.1
	B	263	259.1 (4.7)	4.2%	0.2
	C	875	874.8 (7.4)	2.7%	0.0
	D	556	556.6 (3.6)	1.9%	0.0
	E	927	921.3 (7.8)	1.9%	0.2
	F	1,208	1,201.8 (11.6)	2.2%	0.2
	G	392	394.2 (5.7)	3.4%	0.1
	H	515	516.8 (6.1)	3.1%	0.1
	I	679	674.0 (9.6)	3.3%	0.2
	J (NS)	346	348.2 (4.9)	4.5%	0.1
	K (SN)	364	367.2 (4.2)	2.6%	0.2
	L (SN)	447	443.9 (4.8)	1.1%	0.2
	M (NS)	517	522.5 (6.4)	2.8%	0.2
	N (NSE)	1,265	1,261.6 (8.6)	1.5%	0.1
Evening peak hour	A	1,199	1,191.1 (11.2)	3.0%	0.2
	B	837	833.3 (9.4)	2.5%	0.1
	C	986	977.6 (12.1)	2.8%	0.3
	D	354	357.1 (4.9)	3.0%	0.2
	E	1,070	1,077.6 (8.4)	1.7%	0.2
	F	1,189	1,186.7 (6.3)	1.7%	0.1
	G	481	478.9 (7.2)	3.3%	0.1
	H	750	754.1 (5.5)	1.6%	0.2
	I	373	372.7 (3.8)	2.2%	0.0
	J (NS)	589	594.3 (5.5)	2.9%	0.2
	K (SN)	980	976.1 (6.4)	1.3%	0.1
	L (SN)	939	928.9 (6.5)	1.6%	0.3
	M (NS)	920	916.1(6.9)	1.5%	0.1
	N (NSE)	1,880	1,873.4 (10.4)	0.9%	0.2

Notes. N—north direction; S—south direction; SN—northwest to southeast direction; NS—southeast to northwest direction; NSE—northeast to southwest direction.

Table 5. Observed and simulated travel time and mean speed (calibrated parameters) during the morning peak hour.

Parameter	Route	Sample size (N_{MIN})	Observed (95%CI)	Simulated (95%CI)	*GEH* statistic
Travel time (seconds)	1	10 (6)	311.6 (15.9)	309.6 (5.0)	0.1
	2	16 (14)	191.2 (11.0)	188.7 (3.7)	0.2
	3	8 (4)	410.7 (7.8)	400.3 (5.3)	0.5
	4	8 (2)	288.3 (12.4)	286.8 (3.8)	0.1
Speed (km/h)	1	10 (6)	18.1 (0.8)	19.0 (0.7)	0.2
	2	16 (14)	25.8 (0.1)	26.4 (0.7)	0.1
	3	8 (4)	15.0 (0.5)	15.7 (0.4)	0.2
	4	8 (2)	19.8 (0.8)	20.3 (0.5)	0.1

peak, evening peak, and both time periods in the selected case study are presented and analyzed (see section 3.2).

3.1 Model calibration and validation

As suspected, the first runs using VISSIM default parameters proved that there are differences between observed and simulation values of performance measures. The results from VISSIM for both travel times and average speed are presented in Table 3, using model default parameters and a number of floating car runs (N_{MIN}) higher than recommended by Dowling et al. (2004). It was clear that the simulated values intervals did not include observed values intervals (Dowling et al., 2004). Similar results were recorded from the comparison between observed and simulated speed counters data on several arterials of the study domain. VISSIM also presents several limitations on acceleration/deceleration rates modeling, namely: (a) acceleration/deceleration profiles are not modeled as speed profiles (a range of values) (PTV, 2011); (b) predicted acceleration is overestimated in relation to observed data (Fellendorf & Vortisch, 2010); and (c) when vehicles attain their desired speed in free driving conditions, they tend to drive at constant speed (PTV, 2011; Wiedemann, 1974), which is not observed in reality. Accordingly, additional efforts to adjust calibration parameters are needed.

Considering the driver behavior parameters of the traffic model, we excluded lane-change and simulation resolution. In the first case, we found that lane change parameters do not impact vehicle speeds. Concerning simulation resolution parameter, by default its value is 1 time step/(sim.s) in the VISSIM traffic model, which corresponds to a time step of 0.1 s for vehicle records data (instantaneous speed, acceleration/deceleration). Then, we used a value of 10 time steps/(sim.s) in order to fit the time resolution of traffic model and VSP emission model input (a second-by-second basis).

In order to minimize the impacts of VISSIM limitations and to increase the reliability of VISSIM to predict on-road speed and acceleration profiles, we carried out some procedures

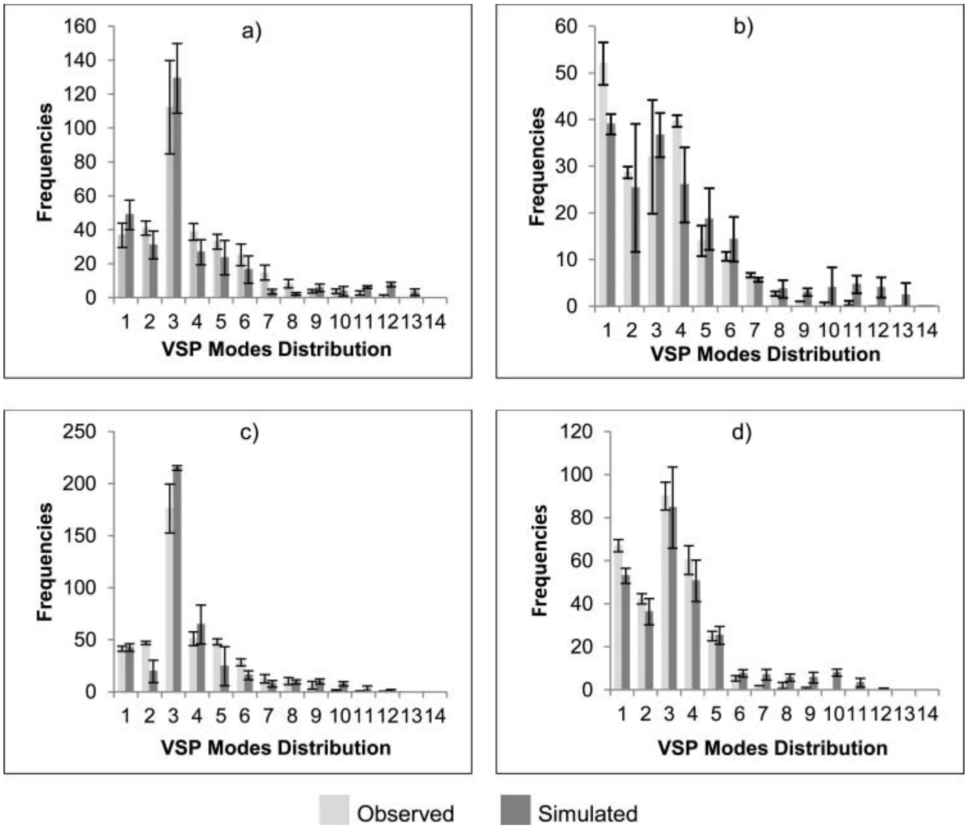

Figure 4. Average and standard error VSP modes distribution for observed and simulated data: (a) route 1; (b) route 2; (c) route 3; (d) route 4.

during the modeling of the baseline scenario. First, we used successive speed limits after or before a reduction area to smooth as much as possible the acceleration and deceleration values. Second, the authors use speed limits in several sections of the arterial with a difference up to 3 m/s (more or less) to avoid constant speeds.

By using the golden section method as a searching algorithm for the optimal parameter value (Dowling et al., 2004) we selected 1.70 and 2.80 values for the additive and multiple part of safety distance, respectively, and selected a value of 1.25 meters for average standstill distance. Given the nature of this study, we decided to conduct 10 initial simulation runs (Hale, 1997) for each time-period scenario.

The comparison between simulated and observed hourly traffic flows for both morning and evening peak hours is provided in Table 4 for 10 initial random seed runs. The GEH statistic test for traffic flows for each counter was significantly less than 4 and RMSE rates did not exceed 5% in the two time periods. These validation results meet the hourly flow criteria in Dowling et al. (2004) and FHWA Travel Mode Improvement Program (2010).

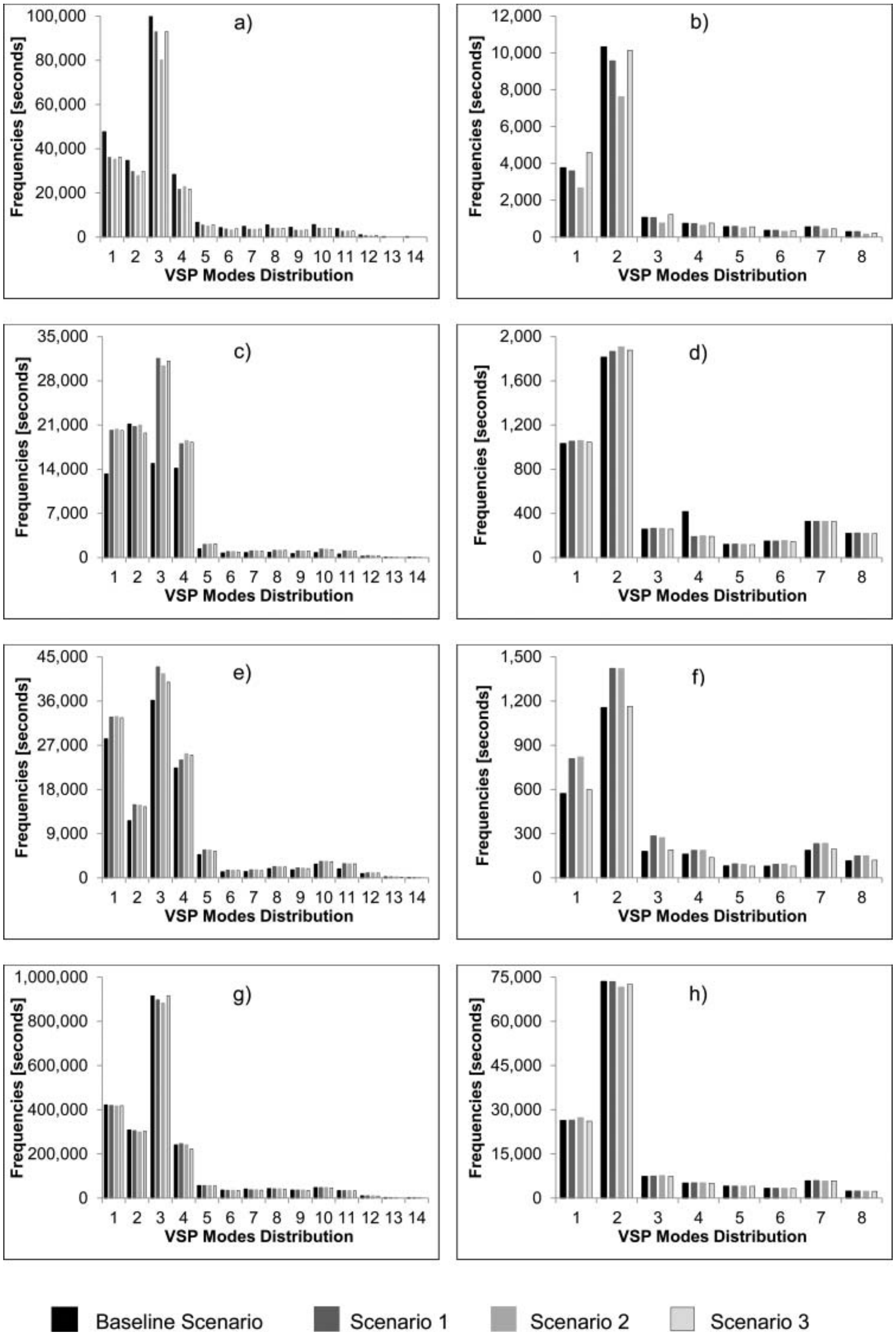

Figure 5. Average VSP modes distribution for each scenario during the morning peak hour (7–8 a.m.): (a) LDV in LA; (b) transit buses in LA; (c) LDV in AR1; (d) transit buses in AR1; (e) LDV in AR2; (f) transit buses in AR2; (g) LDV in ON; (h) transit buses in ON.

Table 5 shows the comparison of travel times and speed profiles for the morning peak hour. For those parameters, we achieved GEH values ranging from 0.1 to 0.5, considering a number of floating car runs (N_{MIN}) higher than recommended by Dowling et al. (2004). These results also indicated a good accuracy of traffic modeling process and they were much better than those obtained using default parameters (Table 3). Analyses of the acceleration and speed estimation values in several points of selected routes resulted in the same conclusions as the above measures.

Figure 4 illustrates the VSP mode distributions of observed and simulated frequencies for each route performed. We observed that VSP mode 3 is more prevalent on routes 1 (see Figure 4.a) and 3 (see Figure 4.c). This can be explained by the higher number of traffic signals on both routes that led to more vehicle stops. The differences between the two VSP distributions arise in mode 3, in which vehicles from simulation are stopped for a longer time at traffic lights. In spite of having more prevalence on VSP modes higher than 5 (higher acceleration rates) and 1 and 2 (higher deceleration rates) on simulated data, we recorded a good fit between observed and simulated data sets of VSP modes distributions. The results of K-S statistic test results at a 5% significance level (*D*-value) with respect to the VSP distribution for routes 1 to 4 were, respectively, 0.086 (p-value $= 0.15$), 0.131 (p-value $= 0.12$), 0.068 (p-value $= 0.28$) and 0.100 (p-value $= 0.08$) (Pearson, Pearson, & Hartley, 1966). This means that two VSP modes distribution are drawn from the same distribution. Concerning CO_2 emissions, the relative difference ranges from 7% to 18%. For each route performed, we did not find significant differences on means samples (p-value > 0.05). Analyses of the CO, HC, and NO_X emissions per vehicle resulted in the same conclusions as the CO_2 emissions.

3.2 VSP modes distribution, emission rates, and traffic performance parameters

In this section, we compare VSP modes distribution (LDV and transit buses), emissions (CO_2, CO, NO_X, and HC) and traffic performance parameters (number of vehicles, number of vehicles stops, and delays) of the three traffic restriction scenarios in relation to the calibrated baseline scenario. The results are presented for LA area, for AR1 and AR2, and for the ON during the morning and evening peak hours and all vehicular emissions during the two time periods are considered.

3.2.1 Morning peak hour

Figure 5 (a–h) illustrates the average time spent in each VSP mode for each scenario and zone for the morning peak hour.

On average, LDV spent most of the time on VSP modes 1 and 3 while transit buses spent most of the time on VSP modes 1 and 2. All traffic restriction scenarios recorded lower frequency of VSP mode 3 (idling or low-speed situations) for LDV in the LA (see Figure 5-a). On that zone, Scenario 2 achieved the lowest frequency of VSP mode 3 in LDV and VSP mode 2 in transit buses (idling or low-speed situations). As expected, all traffic restriction scenarios yielded higher frequencies of VSP bins on both alternative roads (AR1 and AR2) in comparison to the baseline scenario (see Figure 5 c–d and Figure 5 e–f). This was particularly noticeable on the VSP modes associated with high deceleration/acceleration rates and idling situations. Concerning the ON, we did not find significant differences on the frequency of VSP modes among scenarios evaluated (see Figure 5 g–h). In particular, the bus-only lane also provided less idling and low speed situations (for both LDV and transit buses).

The emissions and traffic performance results on the morning peak hour are summarized in Table 6 for both baseline and traffic restriction scenarios.

Scenario 1 yielded a significant reduction in emissions, reaching similar CO_2, CO, and HC rates as scenario 2, with 29%, 30%, and 27%, respectively. Although the number of vehicles stops is reduced by 20%, traffic delays are decreased by only 5%. This is due to the reduction in the service road's capacity from 2 to 1 lane in that scenario. It was found that scenario 2 gave the best emissions scenario for the LA area, mainly in terms of CO_2 and CO emissions with reductions of 30% and 32%, respectively. The traffic performance measures also

Table 6. Variation of emissions and traffic performance parameters per location in relation to the baseline scenario, during the morning peak hour (7–8 a.m.).

		Emissions (kg)				Traffic performance		
Area	Scenario	CO_2 (kg)	CO (kg)	NO_X (kg)	HC (kg)	Traffic flow (vph)	Number of stops	Delay (s)
LA	Baseline	9.1×10^5	3.2×10^3	4.1×10^4	7.9×10^2	1,732	2,543	15.9
	1	−29%	−30%	−22%	−27%	−14%	−20%	−5%
	2	−30%	−32%	−29%	−27%	−15%	−22%	−26%
	3	−25%	−28%	−26%	−24%	−16%	−19%	−22%
AR1	Baseline	4.6×10^4	1.5×10^2	2.3×10^2	3.5×10^1	346	354	10.7
	1	+91%	+99%	+53%	+121%	+35%	+88%	+85%
	2	+91%	+98%	+55%	+120%	+35%	+88%	+86%
	3	+92%	+99%	+56%	+122%	+36%	+88%	+89%
AR2	Baseline	2.1×10^5	8.3×10^2	6.5×10^2	1.8×10^2	922	813	5.8
	1	+33%	+33%	+37%	+30%	+13%	+15%	+42%
	2	+33%	+32%	+36%	+30%	+12%	+14%	+42%
	3	+29%	+30%	+35%	+28%	+12%	+15%	+43%
ON	Baseline	2.7×10^7	9.8×10^4	1.2×10^5	2.5×10^4	6,241	36,278	15.9
	1	−0.7%	−0.1%	−0.1%	−0.5%	0.0%	−0.6%	+32.5%
	2	−0.9%	−0.8%	−0.2%	−0.8%	0.0%	−1.0%	+22.1%
	3	−0.4%	−0.1%	−0.1%	−0.3%	0.0%	−0.3%	+25.0%

Q2 Notes. LA: Liberdade Avenue; AR1: Alternative Road 1; AR2: Alternative Road 2; ON: Overall Network.

indicated scenario 2 as the better solution with the number of stops and delays reduced by more than 20%. These findings confirm the values presented in Figure 5 (a–b) in which the bus-only lane scenario achieved the lowest frequency of VSP modes 3 and 2 for LDV and transit buses, respectively. The effects of closing central roads to traffic (Scenario 3) were smaller than the effects of the bus-only lane. This was clear both in terms of emissions and traffic performance measures.

As expected, AR1 showed an increase of vehicular emissions of more than 90% for CO_2, CO, and HC in all evaluation scenarios. Despite the increase in vehicles' volumes by 35%, both vehicles' stops and delays increased by almost 90%. In this case, AR1 is a single-lane road with several traffic lights on its boundaries that do not allow higher green times. It should also be mentioned that idle emissions on traffic restriction scenarios increased substantially (+109%) compared to the baseline scenario.

Concerning AR2, the effect of traffic diversion was most noticeable on NO_X emissions with a substantial rise of almost 40%, while the number of stops and delays also increased by

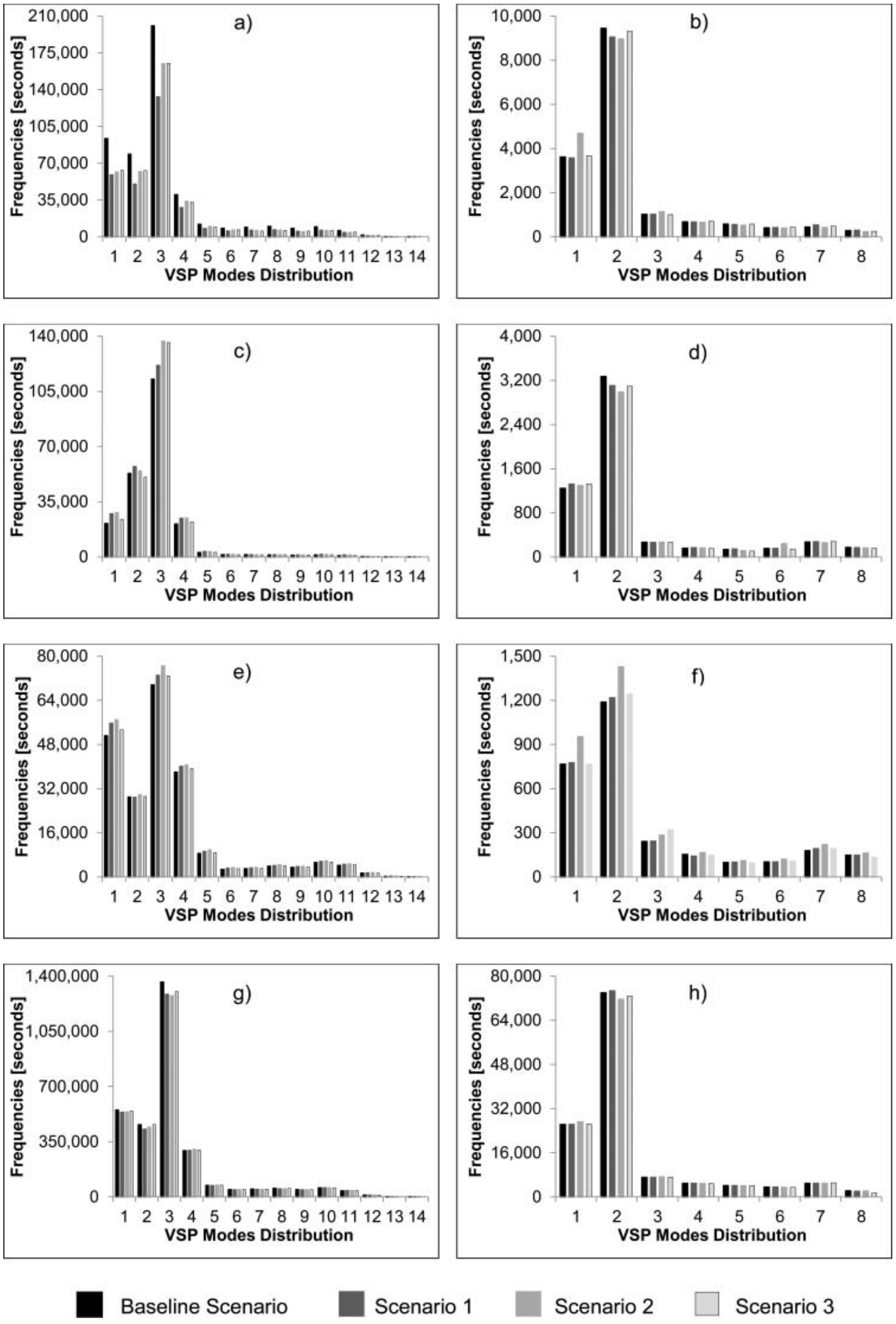

Figure 6. Average VSP modes distribution for each scenario during the evening peak hour (5–6 p.m.): (a) LDV in LA; (b) transit buses in LA; (c) LDV in AR1; (d) transit buses in AR1; (e) LDV in AR2; (f) transit buses in AR2; (g) LDV in ON; (h) transit buses in ON.

15% and 40%, respectively. If we considered only idle emissions, the percentage increase in traffic restriction scenarios exceeded 178% compared to the baseline scenario.

Considering the ON, the effects on emissions of traffic restriction measures were found to be rather small. VSP modes distributions were similar among scenarios (see Figure 5 g–h). Scenario 2 gave the highest CO_2 emissions reduction by 1%, corresponding to almost 240 tons per hour. Furthermore, it also showed improvements in terms of CO and HC emissions savings of 0.8%, while NO_X slightly decreased by 0.2%. For traffic measures, all scenarios yielded smaller reductions in vehicle stops, while delays increased in more than 20% of scenarios.

3.2.2. Evening peak hour

Figure 6 displays the VSP modes distribution for each scenario during the evening peak period in LA area, AR1, AR2, and ON. The frequency of VSP modes 1, 2, and 3 for LDV in all traffic restriction scenarios decreased considerably compared with the baseline scenario (see Figure 6-a). Considering the alternative roads, we observed that traffic diversions from LA lead to an increase in the number of LDV stops (more VSP mode 3). Note that all vehicle types tend to have higher deceleration rates on these areas (see Figures 6-c and 6-e). For transit buses, as illustrated in Figures 6-d and 6-f, we did not observed substantial differences on VSP modes distribution among scenarios. This can be explained by the minor contribution of this vehicle type (<5%) on fleet composition. When analysis extended to the ON, the impact of traffic restriction measures became more expressive in comparison to the morning peak hour. In particular, the dropping of one lane (scenario 1) achieved the lowest number of vehicle stops and low speed situations on both LDV and transit buses (see Figure 6 g–h).

Scenario 1 was the best mobility solution in terms of emissions. It had an average CO_2, CO, and HC emissions reduction of about 50% and recorded the smallest number of vehicle stops, with 33% (see Table 7). This is explained by its good environmental and traffic performance on both time periods mainly in the evening peak hour even if considering the higher traffic flow on the northbound lane during that period. Despite its environmental benefits improvement, this scenario is shown to be less effective in terms of delays compared to others traffic restriction scenarios as a result of the high ratio between traffic flows and capacity on the service roads that are restricted to one lane. Scenarios 2 and 3 yielded similar emission reductions on the LA area (see Table 7), with the exception of HC pollutant. Specifically, the bus-only lane implementation allowed hydrocarbons to be reduced by 47%.

The average increase in emissions ranged from 27% to 30% between scenarios 1 and 3 for a traffic flow increase between 10% and 11%. Particularly relevant was the increase in stops (see Figure 6 c–d), reaching 76% for scenario 2. From these results, it was clear that vehicles avoided the use of AR1 as a path for their trips, in spite of the lower capacity imposed on LA.

AR2 also yielded increased emissions in all restriction scenarios, namely, 25% for NO_X and around 20% for CO_2, CO, and HC, in both scenarios 2 and 3. The changes in traffic performance parameters were less dramatic. In this case, the number of stops increased 12%, while delay increased by 16% and 18% for scenarios 1 and 2, respectively. Although idle emissions produced on traffic restriction scenarios sharply increased 15% and 6% in AR1 and AR2, respectively, in comparison to the baseline scenario, they alone contributed with 40% and 17% of the total emissions.

Considering the ON, the impact of traffic restriction scenarios was more significant in comparison to the morning peak hour conditions. These results were in accordance with VSP modes distribution presented previously for LDV (see Figure 6-g). Scenario 1 provided the lowest vehicular emissions for all pollutants analyzed. In this case, we recorded emissions reductions of 4.1%, 3.2%, 7.6%, and 4.1% for CO_2, CO, NO_X, and HC, respectively. Moreover, scenario 1 also yielded fewer stops, with a reduction of 2.4%. As suspected, the traffic diversion had effects on delays in all restriction scenarios with increases close to 20% due to some traffic congestion on alternative roads. Doubtless, these values point out the potential negative impacts of the measures evaluated here in some stretches of the selected case study area.

Table 7. **Variation of emissions and traffic performance parameters per location in relation to the baseline scenario, during the evening-peak hour (5–6 p.m.).**

		Emissions (kg)				Traffic performance		
Area	Scenario	CO_2 (kg)	CO (kg)	NO_X (kg)	HC (kg)	Traffic flow (vph)	Number of stops	Delay (s)
LA	Baseline	2.2×10^6	7.6×10^3	7.4×10^3	2.3×10^3	2,464	5,473	35.7
	1	−48%	−49%	−38%	−51%	−24%	−33%	−24%
	2	−44%	−46%	−34%	−47%	−27%	−28%	−31%
	3	−44%	−45%	−34%	−44%	−26%	−28%	−29%
AR1	Baseline	1.8×10^5	5.1×10^2	5.5×10^2	2.4×10^2	563	1211	94.6
	1	+23%	+28%	+22%	+34%	+10%	+74%	+33%
	2	+27%	+29%	+24%	+36%	+11%	+76%	+34%
	3	+31%	+30%	+25%	+35%	+11%	+75%	+34%
AR2	Baseline	6.1×10^5	2.4×10^3	1.7×10^3	5.5×10^2	1,483	1,581	9.9
	1	+17%	+18%	+16%	+16%	+11%	+12%	+16%
	2	+22%	+22%	+25%	+20%	+12%	+12%	+18%
	3	+21%	+21%	+25%	+19%	+12%	+12%	+18%
ON	Baseline	4.1×10^7	1.4×10^5	1.5×10^5	4.1×10^4	7,245	63,081	87.3
	1	−4.0%	−3.2%	−7.6%	−4.1%	+0.2%	−2.4%	16.3%
	2	−2.6%	−2.2%	−3.5%	−3.9%	+0.1%	−2.3%	17.6%
	3	−2.2%	−1.2%	−3.5%	−3.4%	+0.1%	−1.3%	18.5%

Notes. LA: Liberdade Avenue; AR1: Alternative Road 1; AR2: Alternative Road 2; ON: Overall Network.

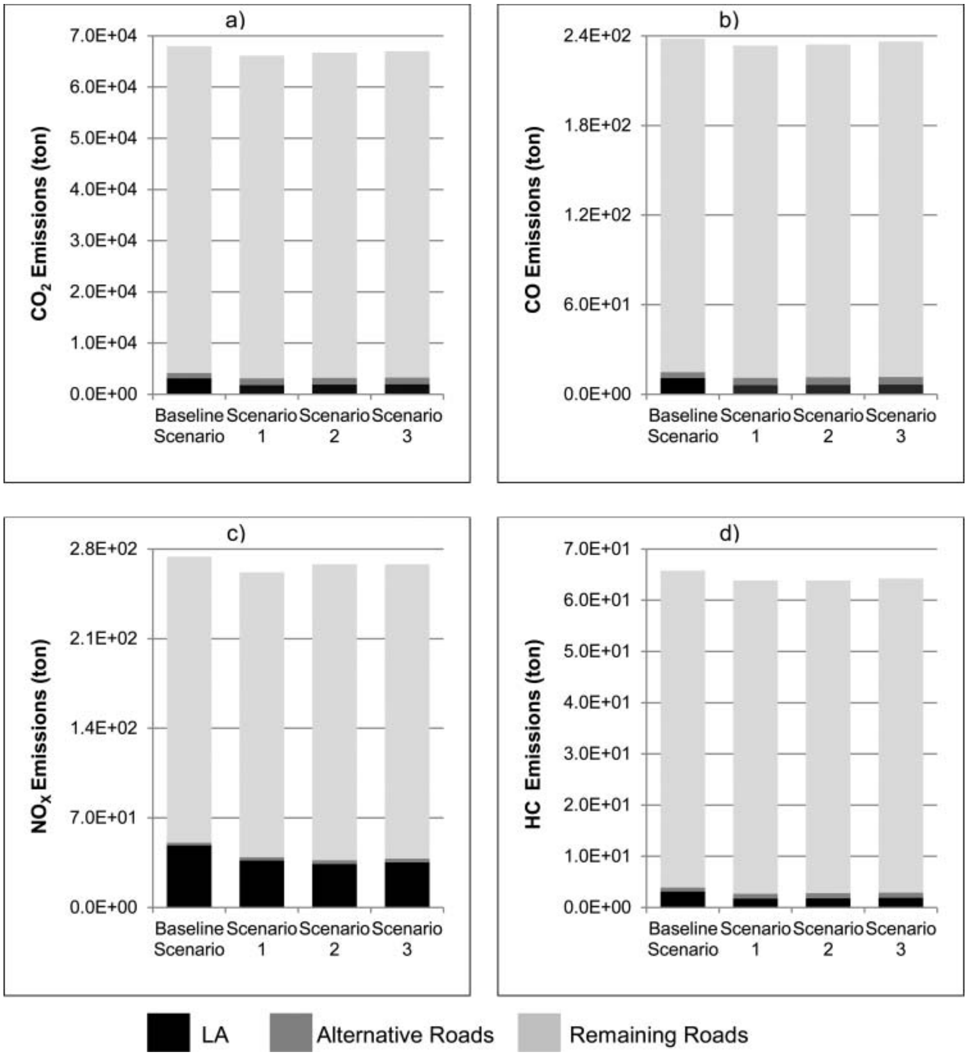

Figure 7. Total of emissions (ton) of the two time periods per scenario: (a) CO_2; (b) CO; (c) NO_X; (d) HC.

3.2.3 Two time periods

Figure 7 plots the total emissions produced by two time periods for the baseline and all traffic restriction scenarios. From a CO_2 criterion, scenario 1 gave the best emissions scenario for the overall network, with about 4% reductions in comparison to scenarios 2 and 3. This corresponds to more than 2,000 tons of CO_2 emitted during the two time periods. Analyses of the local pollutants associated with traffic resulted in the same conclusions as the CO_2 emissions. The results presented in Figure 7 also show that the emissions contribution of the LA and AR1 and AR2 was rather small on the ON. This was particularly visible on CO_2, whose emissions contribution from the three above areas did not exceed 5% in all traffic restriction scenarios.

4. Conclusions

This paper provides a methodological framework for the assessment of multiple traffic restriction measures on vehicular emissions and traffic performance parameters using a microscopic traffic simulation model combined with an emission model. The case study considered was an urban arterial with two central roads. A limited number of alternative paths were also taken into account.

The main conclusions of this research are:

- For the morning peak hour, the highest average emissions reduction predicted on LA are associated with bus-only lane seal at 30%;
- Dropping one through lane is shown to be the best mobility scenario for LA during the evening peak hour during which average emissions reductions reached 47%;
- Traffic diversions contributed to additional congestion on alternative roads and increased emissions in those areas, namely for CO_2, CO, and HC emissions, with increases of more than 90% above the baseline scenario;
- Considering the ON and summing the emissions contribution of the morning and evening peak periods, the drop of one lane is the best mobility solution.

Therefore, it can be argued that the findings of this paper confirm some of previous studies. Note that the methodology can be generalized to other urban arterials with similar traffic flows. Moreover, this methodology can be tailored to assess other traffic restriction policies in real-world case studies that have already been implemented, and whose impacts were not thoroughly evaluated. Because of the importance of more before and after studies to address their environmental and traffic performance impacts on real-world case studies, the methodology presented in this research is also useful for similar analysis. Nevertheless, there are some limitations that must be highlighted. One of them is the exclusion of traffic incidents (such as collisions or work zones) on the comparison among different traffic measures. Another limitation is the lack of dynamic route selection that takes into account an environmental criterion. Currently, traffic models use distance, time, and cost functions to assign vehicle routes across the network. A traffic assignment procedure taking into account environmental criteria could optimize the effects of traffic restriction measures on the overall network (Bandeira et al., 2013). The third limitation concerns the exclusion of the Heavy Duty Vehicles. It must be emphasized that in the study domain, this class represented less than 1% of road traffic. However, in the cases with a higher percentage, it must be considered that the driving patterns of this vehicle type are different from Light Duty Vehicles, which could have a significant effect on emissions and traffic performance.

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