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Comparison of exhaust emissions at intersections under traffic signal versus roundabout control using an instrumented vehicle

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Abstract

The traditional approach to the comparison of alternative types of road intersection control has focused mainly on efficiency and safety. In recent years, the increasing importance of air pollution produced by vehicular traffic has suggested that environmental considerations should be added to the above aspects as a criterion for intersection design. This study describes a before-and-after analysis conducted on a road intersection where a roundabout has replaced a traffic signal. Using a Portable Emission Measurement Systems (PEMS) installed on a test car, the instantaneous emissions of CO_2, NO_X and CO have been measured over repeated trips along a designated route. A total of 396 trips have been carried out in different traffic conditions and in opposite directions along the chosen route. Using statistical methods the existence of significant differences in emissions attributable to the type of intersection control has been investigated based on the experimental data. The results indicate that replacing the traffic signal with the roundabout tends to reduce CO_2 emissions, even if the differences are not always statistically significant; on the contrary, the signalized intersection performs better in terms of NO_X emissions. Finally, results are less clear for CO emissions, and differences are statistically non significant in most cases.

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Keywords: Air Quality; Emissions; Intersection Control; Traffic Signal; Roundabout; PEMS

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1. Introduction

Air pollution produced by vehicular traffic is receiving increasing attention in the context of traffic management and control research and practice. Vehicular emissions depend on traffic, road and vehicle characteristics, on atmospheric conditions and on driving behavior. Intersections are critical elements of road networks in terms of air quality impact, and their control type and geometric configuration can affect significantly vehicular emissions (Matzoros and Van Vliet, 1992; Pandian et al., 2009). At intersections vehicles usually slow down and often stop, thus interrupting traffic flow in varying patterns. Several studies have shown that roundabouts are safe and efficient and can improve traffic flow compared to other types of intersection control (Federal Highway Administration, 2010); however, there is no general agreement regarding their ability to reduce vehicular emissions and fuel consumption.

The main aim of this study is to compare the environmental performance of a roundabout and a signal-controlled intersection using a before-and-after approach. More specifically, a real road intersection where a roundabout has replaced a signal-controlled intersection has been analyzed, and the two forms of control have been compared in terms of emissions of three major pollutants (CO_2, CO, and NO_X) based on data collected on-road using an instrumented vehicle.

The paper is organized as follows. Section 2 summarizes previous work on vehicular emissions in relation to vehicle dynamics, with specific attention to the environmental impacts of intersections under different kinds of control. Section 3 describes the study site, the alternative types of intersection control tested in the study (roundabout vs. traffic signal), and the characteristics of the test vehicle and equipment. Section 4 explains the methodologies adopted to collect and treat experimental data, while Section 5 reports the results of the comparative analysis of emissions under traffic signal versus roundabout control. Concluding remarks and possible future developments of the research are presented in Section 6.

2. Previous work

Several studies dealing with the analysis of vehicular emissions at road intersections can be found in the literature, some of them focusing in particular on the effect of the type of traffic control on emissions. A short review of such studies is presented in this section, preceded by references to a few papers analyzing the relationship between emissions and vehicle dynamics. Some of the studies considered in this section are based on a modeling approach, often combining traffic microsimulation models and vehicular emission models, while others are based on direct field collection of emission data, typically using Portable Emission Measurement Systems (PEMS).

2.1. Studies on the relationship between emissions and vehicle dynamics

Tong et al. (2000) studied on-road pollutant emissions and fuel consumption in urban driving conditions using four instrumented vehicles of different types. One of their main conclusions was that the transient driving modes (acceleration and deceleration) were more polluting than the steady-speed driving modes (cruising and idling). Ahn et al. (2002) developed several microscopic models relating emission rates of CO, HC and NO_X to instantaneous speed and acceleration of vehicles, and emphasized the value of this approach for estimating the environmental impact of operational-level projects. Frey et al. (2003) developed and demonstrated a systematic procedure for the determination of modal emission rates using PEMS. They found, in particular, that average emissions during acceleration are typically five times greater than during idle for HC and CO_2 and ten times greater for NO_X and CO. Unal et al. (2004) focused on the identification of emission "hot spots", that are fixed locations along a highway where emissions in peak conditions are considerably higher (by more than a factor of two) than in free-flow (or near free-flow) conditions. Using data collected with PEMS, they explored the relationships between hot spots and several explanatory variables. Song et al. (2012) evaluated the applicability of the microscopic traffic simulation model VISSIM for the purpose of estimating vehicular emissions. Using the distribution of Vehicle-Specific Power (VSP) as explanatory parameter of emissions, they concluded that the simulated VSP distribution is not representative of real-world vehicle dynamics, and is not sensitive to the parameters commonly used for model calibration, thus leading to significant errors in estimated emissions. Jie et al. (2013) calibrated the behavioral parameters of VISSIM that affect speed and acceleration patterns based on real vehicular trajectories, and showed that using the default settings of these parameters could lead to significant errors in the calculation of emissions. In order to evaluate the accuracy of the VISSIM microsimulation model in providing realistic estimates of vehicle activity as input to MOVES, Oneyear and Hallmark (2013) compared speed and acceleration data collected using an instrumented vehicle along a test corridor with the output of a VISSIM implementation on the same corridor, and found statistically significant differences between field and simulated VSP distributions. Ying et al. (2016) investigated the effect of work zone pavement roughness on vehicular emissions using field data collected with PEMS, and calibrated an emission factor model based on operating mode identification. Their findings indicate that the effect of pavement roughness on emissions is different depending on the type of pollutant. Li et al. (2016) further analyzed the relationship between emissions and pavement roughness using cluster analysis, and found a nonlinear relationship suggesting that emissions are lower for intermediate values of surface roughness.

2.2. Studies on vehicular emissions at intersections

The impacts of specific types of intersection control on pollutant emissions have been analyzed in several studies. Based on a before/after study, Hyden and Varhelyi (2000) and Varhelyi (2002) found that small roundabouts replacing unsignalized intersections caused a limited increase in CO and NO_x emissions, while small roundabouts replacing signal-controlled intersections led to a considerable decrease of emissions of the same pollutants. Zuger et al. (2001) used an instrumented vehicle to carry out a before/after study on five intersections that had been converted to roundabouts. They found that the effect of the type of control on emissions depended very much on local conditions and time of day, and therefore no general conclusion could be reached. However, a tendency of roundabouts to perform better than signalized intersections and worse than unsignalized intersections was observed in their study. Unal et al. (2003) studied the impact of traffic signal timing and coordination on vehicular emissions using on-road measurements collected on two signalized arterials in Cary, North Carolina. Their findings confirm the effectiveness of signal coordination as a tool for reducing emissions. Coelho et al. (2006) developed a relationship between vehicle dynamics and emissions for single-lane roundabouts, based on synthetic speed profiles and their frequency distribution as a function of congestion levels. Mandavilli et al. (2008) used the aaSIDRA 2.0 software to analyze emissions at six intersections where roundabouts had replaced two-way or four-way stop control. They found a statistically significant decrease in CO, CO_2, NO_X and HC emissions as a result of roundabout installation. Ahn et al. (2009) conducted an environmental assessment of a high-speed roundabout in comparison with two-way stop control and signal control using traffic microsimulation and microscopic emission models, and concluded that the roundabout does not necessarily reduce emission levels compared to the other forms of intersection control. Chamberlin et al. (2011) compared CO and NO_X emission estimates obtained using the MOVES versus CMEM software in combination with the Paramics microsimulation model. Based on an application to a case of intersection control change (from pre-timed traffic signal to roundabout), they concluded that MOVES and CMEM produce similar NO_X estimates, but differ widely in their estimates of CO. Their results also suggest that a roundabout may perform worse than a pre-timed traffic signal in terms of the pollutants considered in the study, under both light and congested traffic conditions. Tao et al. (2011) used real-world emissions measured with PEMS and GPS data to evaluate the impact of signal coordination on vehicle emissions under two speed scenarios, and concluded that the environmental benefits of coordination decrease as average traffic speed decreases in the transition from non-peak to peak hour conditions. They also found that the effectiveness of coordination in reducing emissions is different depending on the type of pollutant considered, and varies with driving behavior. Hallmark et al. (2011) used a vehicle instrumented with PEMS to collect on-road emission data and compared the air quality impacts of different types of intersection control (signal, four-way stop and roundabout) located along two corridors in Woodbury, Minnesota. Their field tests considered only through movements across the intersections, and refer only to uncongested traffic conditions. Based on the comparative analysis in terms of CO_2, CO, NO_X and HC emissions, the authors concluded that the results varied by type of pollutant and by driver behavior, and that in several cases signal control and four-way stop control performed better than roundabout control. Papson et al. (2012) used the MOVES 2010 software and a time-in-mode analysis to estimate vehicular emissions at a signalized intersection under different traffic scenarios. They concluded that emissions are much less sensitive to congestion than control delay, and that significant environmental benefits can be expected from strategies (like signal coordination) that reduce the time spent by vehicles in the acceleration mode. In order to provide some general indications about the environmental impact of roundabouts in comparison to other forms of intersection control, Jackson and Rakha (2012) studied a "generalized" four-leg intersection with uniform approach demands. They compared emissions of CO, CO_2, HC and NO_X under four types of traffic control (roundabout, signal control, two-way stop control and all-way stop control) using the INTEGRATION software. Their results indicate that roundabouts can minimize the emissions of the considered pollutants only in certain ranges of approach demands and turn percentages. Vasconcelos et al. (2014) adopted a microscopic simulation approach to identify the consequences of converting an existing single-lane roundabout to a two-lane roundabout and after to a turbo-roundabout in terms of capacity, safety and emissions. Concerning pollutants, if the priority is the reduction of CO_2 emissions, a two-lane roundabout is a better choice, but for other local pollutants (CO and HC) turbo-roundabouts appear to offer a better performance. Gastaldi et al. (2014) analyzed a real four-leg intersection located in the Province of Venice (Italy), where a roundabout had replaced a fixed-time traffic signal. Using the microsimulation software S-Paramics and instantaneous emission models for NO_X, PM_{10} and total carbon, they concluded that the roundabout generally outperformed the fixed-time traffic signal in terms of vehicle emissions, although the difference between the two types of control was smaller in terms of environmental impacts than in terms of operational traffic performance. In a recent study, Salamati et al. (2015) developed an empirically supported macroscopic method for comparing vehicular emissions at roundabouts and signalized intersections. Based on VSP (Vehicle Specific Power) as a key explanatory variable, the method allows estimation of emissions of NO_X, CO, CO_2 and HC taking into account several variables, including demand-to-capacity ratio, signal timing and signal progression characteristics. Results of an application to a real case indicate that roundabouts tend to generate less emissions than traffic signals under low demand-to-capacity ratios; however, when demand approaches capacity, signalized intersections with favorable progression produce lower emissions than roundabouts.

3. Case study

3.1. Description of the study site

The study site is a four-leg road intersection where a roundabout has replaced a traffic signal (Figure 1). The intersection is located in the urban area of Vicenza, in the Veneto region, Italy. Basic traffic signal and roundabout characteristics are reported in Tables 1 and 2 respectively.

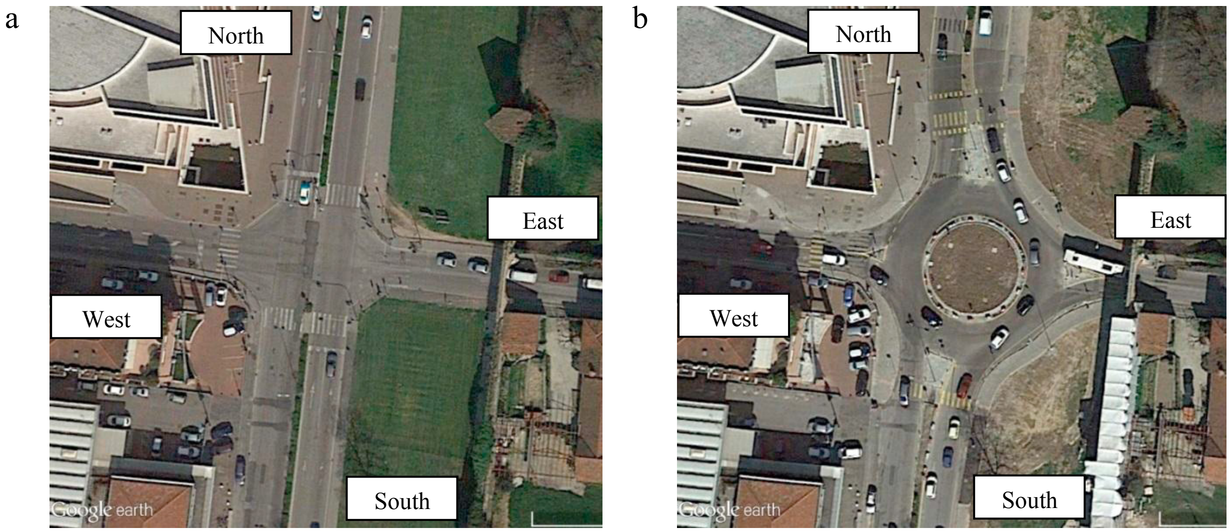

Figure 1. Aerial photograph of the study site: (a) signal-controlled intersection (b) roundabout.

Table 1. Signalized intersection characteristics.

Signal Timing (North-South)					Approach characteristics				
						Approach			
	Green	Amber	Red	Cycle		North	East	South	West
Minimum [s]	49.0	3.0	31.8	85.8	Entering lanes [#]	2	1	2	1
Median [s]	50.1	4.0	46.1	100.1	Exiting lanes [#]	2	1	2	1
Maximum [s]	54.9	4.9	62.1	116.2					

Table 2. Roundabout characteristics.

General characteristics		Approach characteristics				
			Approach			
			North	East	South	West
Inscribed circle diameter [m]	36	Entering lanes [#]	2	1	2	1
Central island diameter [m]	20	Exiting lanes [#]	1	1	1	1
Circulatory roadway width [m]	8	Splitter island width [m]	4.50	3.80	4.20	4.20
Lanes in circulatory roadway [#]	1	Entry width [m]	7.25	4.50	7.25	3.75

3.2. Test vehicle and equipment

Experimental tests were carried out with a Fiat Panda Spark-Ignition (SI) bi-fuel (gasoline/natural gas) passenger car. The car was homologated in 2007 and complies with Euro 4 emission standards. Fiat Panda is Italy's best-selling car and it can be considered the point of reference of the city car segment in Europe. The emissive behavior of this car in urban areas has been characterized by Meccariello et al. (2013). It is equipped with an Original Equipment Manufacturer (OEM) three way catalyst (TWC), which catalyzes the reactions between oxidizing (O_2 and NO_X) and reducing (CO and HC) species present in the exhaust. During the on-road tests the car was fuelled only with commercial gasoline. The odometer reading was about 20,500 km at the beginning of the experimental campaign.

On-board vehicle activity and emissions measurement using Portable Emissions Measurement Systems (PEMS) enable data collection under real-world conditions at any location traveled by vehicles on a second-by-second basis. Many studies have shown that that PEMS equipment is able to provide reliable and accurate on-road emission measurements for light-duty vehicles, even for those that will be certified according to future emissions standards (Weiss et al., 2011). The Emission Laboratory of the Italian Istituto Motori CNR has a long experience in test campaigns (in laboratory and on-road) for the measurement of emissions and fuel economy for different kinds of vehicles (cars, buses, light and heavy-duty trucks, mopeds and motorcycles), taking into account the effect of driving behavior, road type, vehicle load, traffic conditions, engine technology, fuel quality, emission control equipment, etc.

A Semtech PEMS from Sensors Inc. was installed on-board the car for emission testing. This device can produce the vehicle's instantaneous emission profile and estimate the level of emissions produced while the car is running. The equipment consists of a tailpipe attachment, heated exhaust lines, a Pitot tube for measuring the exhaust mass flow and temperature, exhaust gas analyzers, a GPS Garmin 16x, sensors for ambient temperature and humidity, and exhaust pipelines. GPS and weather station have been installed outside on the roof of the vehicle. A tool On-Board Diagnostics (OBD) Matrix from Texa, capable to communicate with the Electronic Control Unit (ECU) of the vehicle, has been connected to the car's OBD socket, to collect with 1 Hz frequency the following parameters: vehicle speed, rpm, gear ratio and engine load. A schematic overview of the PEMS configuration on-board the test vehicle is shown in Figure 2. A video camera (Sony HandyCam) has also been installed on-board to record video images of traffic from the viewpoint of the car driver. PEMS measures the exhaust gas concentrations of the regulated pollutants THC, CO, and $NO/NO_2/NO_X$, as well as of CO_2 and O_2, the exhaust mass flow and the exhaust temperature. All parameters are measured with a time resolution of one second. The mass of the complete PEMS amounts to 280 kg including six external batteries for power supply (Sonnenschein A700 from GNB). By using this configuration, and considering the weight of the driver and a passenger, the car reached its maximum load (Gross Vehicle Weight Rating, GVWR). This set-up allows for relatively long test campaigns of 4 hours duration. The THC measurement is generally carried out with an FID analyzer; due to its high power consumption and also for safety reasons (FID requires a hydrogen/helium mixture), during this experimental campaign it has not been used. However, the correct functioning of the three-way catalyst can also be verified by analyzing CO emissions only. The newest PEM systems have a modular composition, with a separate FID module, which would allow to reduce the weight of the PEMS equipment substantially.

The test protocol for measuring exhaust emissions was as follows:

1. Emissions were measured only in hot conditions (engine fluids and catalytic converter already conditioned);
2. A 45 minutes preconditioning period was necessary to let PEMS reach all the set-points;
3. All the clocks had to be synchronized (Semtech, video camera, OBD tool, 2 laptops);
4. The state of charge of the external batteries had to be kept under control.

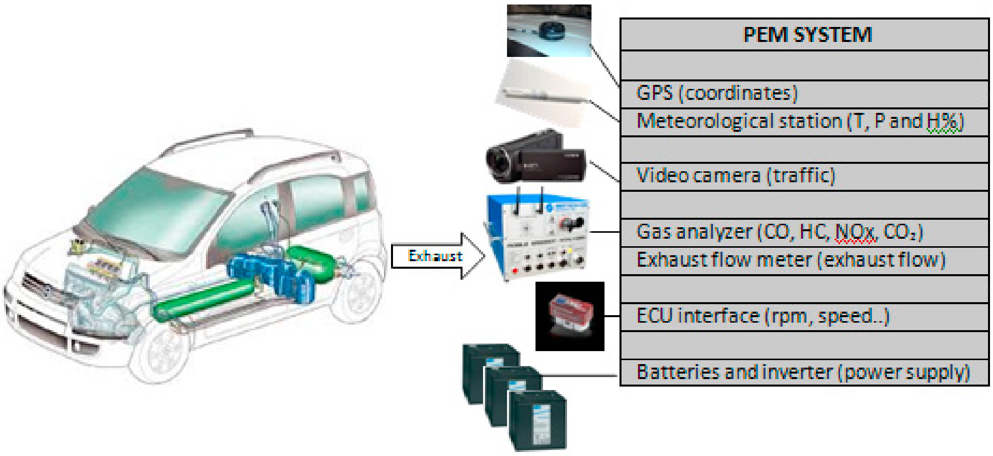

Figure 2. Schematic overview of PEMS and auxiliary components.

4. Data collection and treatment

4.1. Data collection

Two 3-days experimental campaigns were conducted along Viale Mazzini, an urban corridor located in the city of Vicenza, before (April 1-3, 2014) and after (April 14-16, 2015) the conversion of a signalized intersection to a roundabout (Figure 1). In both campaigns, data collection was performed from Tuesday to Thursday.

Morning and evening test sessions were scheduled in two time slots: from 7.00 to 10.30 and from 16.15 to 19.45. Two drivers drove the test vehicle by alternating in one-hour sessions: a 30-year-old man and a 58-year-old woman.

Information on geometric characteristics of the two intersection configurations (see Tables 1 and 2) were collected by field observations, and operational conditions were video-recorded during the experimental campaigns. Using an application software the images were processed extracting the following vehicle-by-vehicle information:

- entering approach;
- type of maneuver at the intersection;
- category of vehicle (car, light goods vehicle, heavy goods vehicle);
- time stamp of the maneuver.

Thirty-minutes intersection O/D matrices were identified by the aggregation of vehicle-by-vehicle data.

Average thirty-minutes total traffic flows for the signalized intersection and for the roundabout were respectively 1447 and 1409 in the morning peak period (7:30-9:00), 1255 and 1220 in the morning off-peak period (9:00-10:00), 1302 and 1331 in the afternoon peak period (17:00-19:30). Since flow data did not show significant changes before and after the conversion of the intersection control, the comparative analysis was considered to be justified. Corresponding average temperature (°C) observed for the signalized intersection and for the roundabout were 12.6 and 15.7 in the morning peak period, 16.9 and 20.5 in the morning off-peak period, 21.3 and 25.7 in the afternoon peak period.

4.2. Data treatment

Before the development of the comparative analysis, data collected during the experimental campaigns were treated as follows.

In order to create a complete dataset, a proper time alignment of all signals acquired by the test vehicle is essential for the calculation and verification of some test parameters as well as for the computation of pollutant emissions. The method used to align families of vehicle parameters consists of:

- A pre-time alignment of ECU data (i.e. engine parameters) and PEMS data using the vehicle ground speed from the ECU and from the PEMS (GPS);
- Time alignment of analyzers with Exhaust Mass Flow (EMF) parameters (CO_2 vs. EMF);
- Time alignment of PEMS (analyzers and EMF) with engine parameters (i.e. rpm vs. EMF).

GPS data were further processed to exclude anomalous and erroneous speed values. Following the suggestions by Rakha et al. (2001), Robust Epanechnikov Kernel (EK) smoothing was applied in combination with an acceleration adjustment model.

To isolate the effect of the type of intersection control on vehicular emissions, an influence study area was identified. It included a 200m segment within the test corridor, subdivided as follows:

- Trip A = test vehicle trip from North to South, from 150m upstream the stop/yield line to 50 m downstream the stop/yield line;
- Trip B = test vehicle trip from South to North, from 150m upstream the stop/yield line to 50 m downstream the stop/yield line;

For each trip, the final dataset (Table 3) includes the following information (1 Hz frequency):

- reference time;
- vehicle position and speed, rpm, gear ratio and engine load;
- instantaneous CO_2 (g/s), CO (mg/s), and NO_X (mg/s) emissions;
- estimated fuel consumption (g/s);
- EMF (kg/h).

As shown in Table 3, the dataset was further subdivided based on other factors, including time of day ("Morning", 7.30-10.00, vs. "Afternoon", 17.00-19.30), traffic condition ("Peak", 7:30–9:00 and 17.00-19.30, vs. "Off-peak", 9.00-10.00), trip direction ("Trip A" vs. "Trip B").

After aggregating the instantaneous data, each trip was characterized by information such as speed profile, total travel time, total pollutant emissions. A total of 396 trips were included in the dataset.

Table 3. Dataset of trips used for the analysis.

Intersection	Morning				Afternoon		Total
	Peak		Off-Peak		Peak		
	TripA	TripB	TripA	TripB	TripA	TripB	
Signalized	32	33	25	24	43	45	202
Roundabout	39	39	27	28	31	30	194
Total	71	72	52	52	74	75	396

5. Comparative analysis of emissions under traffic signal versus roundabout control

The following analyses were conducted to compare the signalized intersection and the roundabout in terms of environmental and operational performance:

- Statistical analysis of total emissions produced (CO_2, CO, NO_X);
- Analysis of emissions by driving mode (acceleration, deceleration, cruise, idle) and type of control;
- Analysis of the relationship between time-in-mode distribution, trip duration and emissions.

5.1. Statistical analysis of total emissions

This analysis evaluates if the average trip total emissions are significantly different for signalized intersection and roundabout, testing the influences of:

- time of day: “Morning” vs. “Afternoon”;
- traffic condition: “Peak” vs. “Off-peak”;
- trip direction: “Trip A” vs. “Trip B”.

Differences between average emissions were evaluated using the Wilcoxon-Mann-Whitney test (significance level $\alpha = 0.05$), since the t-test assumptions were violated in the majority of cases (Table 4).

Table 4. Comparison of CO_2, CO and NO_X trip emissions between signalized intersection and roundabout.

Pollutant	Condition	Signalized Intersection			Roundabout				
		Mean	Median	SD	Mean	Median	SD	Statistic	p-value
CO_2 [g]	Total	59.62	59.88	19.45	51.74	45.46	18.91	W=25173	**<0.001**
	M	58.31	57.95	19.39	48.58	43.49	14.23	W=10105	**<0.001**
	A	61.31	62.28	19.51	58.65	51.85	25.17	W=3060	0.1466
	M-P-TripA	56.03	51.53	21.37	45.22	41.73	9.85	W=809	**0.0324**
	M-P-TripB	63.25	59.15	16.98	57.24	53.84	18.39	W=784	0.114
	M-O-TripA	48.72	48.87	18.95	40.34	38.56	8.73	W=429	**<0.01**
	M-O-TripB	64.53	66.83	16.54	49.13	50.74	10.57	W=529	**<0.001**
	A-TripA	53.49	55.41	19.50	41.32	39.18	9.93	W=915	**<0.01**
	A-TripB	68.79	66.19	16.51	76.57	74.16	23.58	W=553	0.1901
CO [mg]	Total	132.03	88.10	130.73	98.27	78.55	82.53	W=21524	0.0902
	M	116.03	74.50	118.93	106.50	82.14	89.31	W=7421	0.775
	A	152.76	105.76	142.64	80.33	64.96	62.33	W=3439	**<0.01**
	M-P-TripA	184.47	141.03	166.53	108.29	87.80	74.62	W=785	0.0634
	M-P-TripB	123.43	98.01	95.44	129.20	85.04	115.19	W=625	0.8398
	M-O-TripA	65.22	39.17	63.96	92.15	68.25	89.76	W=282	0.3166
	M-O-TripB	67.53	53.75	57.55	86.22	78.85	57.80	W=257	0.1507
	A-TripA	178.28	119.61	161.37	89.86	79.07	64.93	W=849	**0.0457**
	A-TripB	128.39	92.33	118.87	70.49	57.89	58.97	W=893	**0.0184**
NO_X [mg]	Total	60.81	50.78	45.23	90.79	79.14	55.53	W=13255	**<0.001**
	M	46.42	44.01	33.92	82.12	70.80	54.45	W=4513	**<0.001**
	A	79.45	69.81	51.09	109.68	104.58	53.52	W=1875	**<0.01**
	M-P-TripA	38.36	38.48	26.13	66.71	61.33	40.02	W=374	**<0.001**
	M-P-TripB	44.97	33.67	38.77	81.35	68.98	64.05	W=406	**<0.01**
	M-O-TripA	44.17	47.33	34.92	86.01	78.96	50.25	W=171	**<0.01**

M-O-TripB	61.50	57.39	32.11	100.92	81.04	57.56	W=200	**0.012**
A-TripA	64.25	63.65	45.43	85.08	78.63	41.19	W=485	**0.0469**
A-TripB	93.97	92.73	52.45	135.10	137.35	53.43	W=415	**<0.01**

NOTE: Total = complete dataset; M = Morning, A = Afternoon, O = Off-peak, P = Peak
W = Wilcoxon statistic, p-values in boldface indicate statistically significant differences

Considering these results, it can be observed that:

- for CO_2, the roundabout had lower emissions than the signalized intersection for the complete dataset and for all conditions except Trip B runs in the afternoon. However, only some of the differences are statistically significant;
- for CO, the only statistically significant differences are in favor of the roundabout;
- for NO_X, the signalized intersection had lower emissions than the roundabout in all conditions. This result can be explained by considering that the deceleration driving mode, during which the catalytic converter is not always able to fully reduce NO_X, tends to prevail under roundabout control as compared to signal control.

To explain differences in pollutant emissions between the two types of intersection control, the distributions of average trip speeds (km/h) were built using density plots separately for the datasets tested in Table 4 (Figure 3).

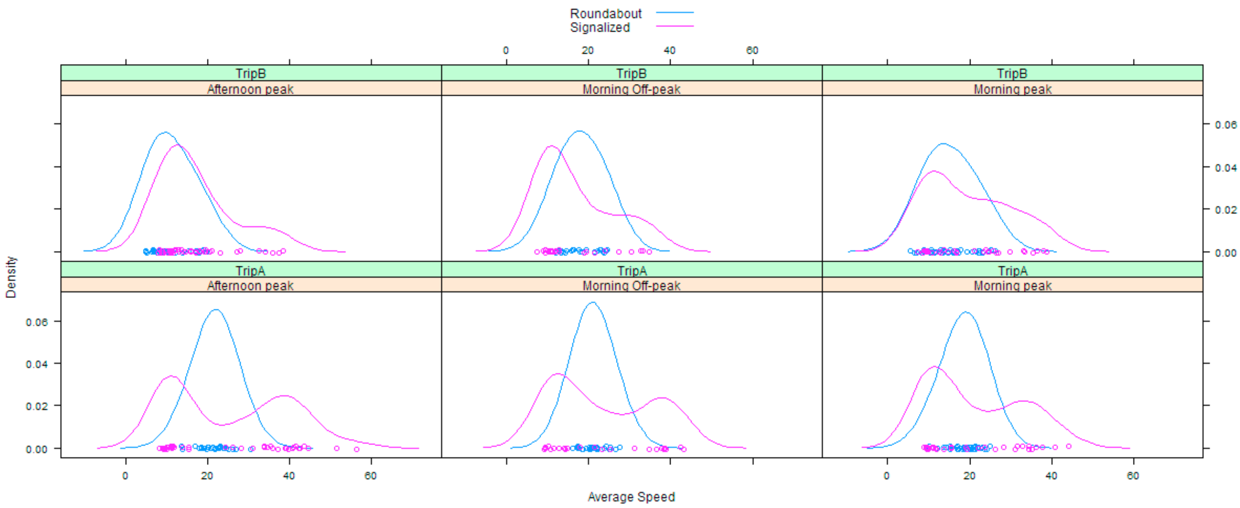

Figure 3. Average trip speed density plots for signalized intersection and roundabout.

As one can observe, for roundabout trips the average speeds tend to follow approximately normal distributions, with higher average speed for TripA conditions, that are representative of better operations than TripB. For the signalized intersection, distributions tend to be bi-modal, especially for TripA data: the higher speeds correspond to cases in which the driver faced the green signal when approaching the intersection, while the lower speeds correspond to cases in which the traffic light was red.

These differences among speed distributions may contribute to explaining differences in total emissions of CO_2, which are more related to trip duration and less affected by trip modal composition. For the other pollutants, the analysis of driving modes is necessary to understand the differences reported in Table 4.

5.2. Average emissions by driving mode and type of control

To analyze in detail the emissions observed for the two types of intersection control, second-by-second emission and speed data associated to each trip were classified according to various driving modes. The four standard driving modes were defined on the basis of the thresholds proposed by Tong et al. (2000); only the definition of "idle" was changed, to consider the effect produced by the smoothing of raw speed data.

Based on the driving modes definition, average instantaneous emission factors were calculated for signalized intersection and roundabout (Table 5), aggregating all trips in the analysis dataset. Substantial differences among instantaneous emission values for the two types of intersection control can be observed in some cases. Results show that for all pollutants under analysis the maximum instantaneous emissions were produced during acceleration and the minimum during idle, with the only exception of CO under roundabout control (for which emissions were highest in cruise mode). For deceleration and cruise, the values are generally intermediate and their relative magnitude depends on the type of control: emissions produced in deceleration mode are higher than those produced in cruise mode for the signalized intersection, but the opposite is true for the roundabout.

Table 5. Driving mode definition and driving mode average instantaneous emission factors for CO_2, CO and NO_X

Driving mode	Speed	Acceleration	CO_2 [g/s]		CO [mg/s]		NO_X [mg/s]		Time in mode [%]	
	[Km/h]	[Km/h/s]	SIG	RBT	SIG	RBT	SIG	RBT	SIG	RBT
Idle	<0.1	<0.1 and >-0.1	0.70	0.67	0.21	0.21	0.08	0.28	12.59	0.86
Acceleration	>0.1	>0.36	2.14	1.39	4.55	2.32	3.15	3.09	34.14	39.93
Deceleration	>0.1	<-0.36	1.11	0.98	3.84	2.06	0.72	1.28	25.80	41.97
Cruise	all other cases		1.04	1.25	1.88	2.69	0.56	1.80	27.47	17.24

NOTE: SIG = Signal control; RBT = Roundabout

5.3. Cluster analysis of the relationship between time-in-mode distribution, trip duration and emissions

Trip data were further processed using cluster analysis with the aim of explaining the relationship between time-in-mode composition of trips, average trip duration and emissions.

Cluster Analysis includes a variety of Data Mining methods used to group objects belonging to a certain dataset on the basis of data similarities (e.g. using Euclidean distance measured in the attribute space). The K-means algorithm (Hartigan and Wong, 1979) is a well-known clustering method; it partitions the objects into *k* groups such that the sum of squared distances from objects to the assigned cluster centers is minimized. The K-means algorithm is used in this study in order to group trips with similar percentages of time spent in each driving mode. The K-means algorithm requires that the number of groups be specified in advance; however, the appropriate number is not known a priori. Therefore, the algorithm was tested by changing the values of *k* from 2 to 20; the best number of groups was chosen based on the values of the Davies-Bouldin Index (1979), and turned out to be 10 for the case study dataset.

The results of the cluster analysis are reported in Table 6, including the average percent time spent in each driving mode, the trip distribution among datasets, the average trip total emissions and the average trip duration.

The following observations can be made based on these results:

- Groups obtained from the clustering method are indicative of the existence of different speed and emission profiles at the intersections:
  - Groups 0, 2 and 7 are characterized by a considerable percentage of "idle" mode; they tend to be typical of the signalized intersection, with long duration and high CO_2 emissions;
  - Groups 1, 3 and 9 are characterized by a high percentage of "acceleration" mode; they tend to be typical of the signalized intersection, with short duration and low to medium levels of CO_2 emissions;
  - Groups 5, 6 and 8 are characterized by a high percentage of "acceleration" and "deceleration" modes, they tend to be typical of the roundabout, with medium duration, low CO_2 emissions and medium to high CO and NO_X emissions;
  - Group 4 is similar to Groups 5, 6 and 8, with trips belonging both to the signalized intersection and to the roundabout.

Table 6. Characteristics of Trip Groups. Average Percent Time Spent in Each Driving Mode, Trip Distribution Among Groups, Average Trip Total Emissions and Average Trip Duration.

Group	Driving mode				Trips					Average Characteristics			
					Signalized		Roundabout		Total	Emissions			Duration
	Acceleration	Cruise	Deceleration	Idle	TripA	TripB	TripA	TripB		CO_2	CO	NO_X	
	[%]	[%]	[%]	[%]	[#]	[#]	[#]	[#]	[#]	[g]	[mg]	[mg]	[s]
Signalized	34.1	27.5	25.8	12.6	100	102	-	-	202	59.62	132.03	60.81	41.75
Roundabout	39.9	17.2	42.0	0.9	-	-	97	97	194	51.75	98.27	90.79	42.51
Group 0	37.2	30.5	27.1	5.2	14	19	-	7	40	65.26	86.28	86.08	49
Group 1	60.0	29.8	11.2	0.0	2	9	-	-	11	45.80	69.02	31.03	19.27
Group 2	25.8	23.7	20.1	30.4	9	13	-	1	23	81.90	119.29	57.26	69.57
Group 3	57.3	13.6	29.3	0.2	13	14	7	7	41	50.92	112.73	64.89	29.24
Group 4	29.4	29.1	40.2	1.3	12	5	6	11	34	51.12	105.75	66.58	40.76
Group 5	48.6	8.1	43.7	0.0	11	4	25	16	56	49.50	153.34	87.70	34.75
Group 6	40.6	18.6	39.8	1.0	9	6	30	34	79	54.28	113.68	97.04	43.22
Group 7	23.4	38.4	21.7	16.6	21	21	-	-	42	76.12	149.07	72.02	64.48
Group 8	33.0	14.0	52.8	0.2	8	1	29	21	59	40.56	93.33	59.26	34.03
Group 9	77.0	7.8	16.0	0.0	1	10	-	-	11	55.16	111.60	70.07	22.55

NOTE: (-) means that the group has no trips

6. Conclusions

This paper has considered the problem of evaluating the relative performance of two alternative intersection configurations (signal control and roundabout) in terms of vehicular emissions. In order to carry out this comparison, a before-and-after study was conducted on a real intersection that had been converted from signal control to roundabout. Emissions of CO_2, CO and NO_X were measured on-road using a PEMS installed on a city car.

The main findings of the study are:

- Replacing the traffic signal with the roundabout has produced lower CO_2 emissions in almost all tested conditions; however, the differences are not always statistically significant.
- NO_X emissions are always lower for the signalized intersection, and the differences are statistically significant in all cases.
- Regarding CO emissions, results are mixed and the differences are statistically non significant in most cases.
- Emissions are generally highest for the acceleration driving mode (with the only exception of CO under roundabout control) and lowest for the idle mode, in agreement with previous studies.
- For all the pollutants considered in the analysis, the type of intersection control has a significant impact on the ranking of the four driving modes in terms of their contribution to the emissions produced.
- This study has demonstrated the usefulness of cluster analysis as a method for exploring the relationship between time-in-mode composition of trips, average trip duration and emissions.

The research described in the present paper could be extended by considering the effects on emissions of factors not taken into account in this study such as, for example, driving style, conflicting pedestrian flows on intersection crosswalks and atmospheric conditions.

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References

Ahn, K., Kronprasert, N., Rakha, H., 2009. Energy and Environmental Assessment of High-Speed Roundabouts. Transp. Res. Rec. J. Transp. Res. Board 2123, 54–65.

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating Vehicle Fuel Consumption and Emissions based on Instantaneous Speed and Acceleration Levels. J. Transp. Eng. 128, 182–190. doi:10.1061/(ASCE)0733-947X(2002)128:2(182)

Chamberlin, R., Swanson, B., Talbot, E., Dumont, J., Pesci, S., 2011. Analysis of MOVES and CMEM for Evaluating the Emissions Impacts of an Intersection Control Change, in: 90th Annual Meeting of the Transportation Research Board. Washington D.C.

Coelho, M.C., Farias, T.L., Rouphail, N.M., 2006. Effect of Roundabout Operations on Pollutant Emissions. Transp. Res. Part D Transp. Environ. 11, 333–343. doi:10.1016/j.trd.2006.06.005

Davies, D.L., Bouldin, D.W., 1979. A Cluster Separation Measure. IEEE Trans. Pattern Anal. Mach. Intell. 1, 224–227. doi:10.1109/TPAMI.1979.4766909

Federal Highway Administration, 2010. Roundabouts: Technical Summary. FHWA-SA-10-006. U.S. Department of Transportation.

Frey, H.C., Unal, A., Rouphail, N.M., Colyar, J.D., 2003. On-road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument. J. Air Waste Manag. Assoc. 53, 992–1002. doi:10.1080/10473289.2003.10466245

Gastaldi, M., Meneguzzer, C., Rossi, R., Della Lucia, L., Gecchele, G., 2014. Evaluation of Air Pollution Impacts of a Signal Control to Roundabout Conversion Using Microsimulation. Transp. Res. Procedia 3, 1031–1040.

Hallmark, S.L., Wang, B., Mudgal, A., Isebrands, H., 2011. On-Road Evaluation of Emission Impacts of Roundabouts. Transp. Res. Rec. J. Transp. Res. Board 2265, 226–233. doi:10.3141/2265-25

Hartigan, J.A., Wong, M.A., 1979. A K-means Clustering Algorithm. Appl. Stat. 28, 100–108.

Hydén, C., Várhelyi, A., 2000. The Effects on Safety, Time Consumption and Environment of Large Scale Use of Roundabouts in an Urban Area: A Case Study. Accid. Anal. Prev. 32, 11–23. doi:10.1016/S0001-4575(99)00044-5

Jackson, M., Rakha, H.A., 2012. Are roundabouts environmentally friendly? An evaluation for uniform approach demands, in: Transportation Research Board 91st Annual Meeting Compendium of Papers. Washington D.C.

Jie, L., Van Zuylen, H., Chen, Y., Viti, F., Wilmink, I., 2013. Calibration of a Microscopic Simulation Model for Emission Calculation. Transp. Res. Part C Emerg. Technol. 31, 172–184. doi:10.1016/j.trc.2012.04.008

Li, Q., Qiao, F., Yu, L., 2016. Clustering pavement roughness based on the impacts on vehicle emissions and public health. J. Ergonomics 6, 1-4. doi:10.4172/2165-7556.1000146

Mandavilli, S., Rys, M.J., Russell, E.R., 2008. Environmental Impact of Modern Roundabouts. Int. J. Ind. Ergon. 38, 135–142. doi:10.1016/j.ergon.2006.11.003

Matzoros, A., Van Vliet, D., 1992. A model of air pollution from road traffic, based on the characteristics of interrupted flow and junction control: Part I - model description. Transp. Res. Part A 26, 315-330. doi: 10.1016/0965-8564(92)90019-4

Meccariello, G., Della Ragione, L., Prati, M.V., Costagliola, M.A., Saccoccia, V., 2013. Real Time Emissive Behaviour of a Bi-Fuel Euro 4 SI Car in Naples Urban Area. SAE Technical Paper 2013-24-0173.

Oneyear, N., Hallmark, S.L., 2013. Evaluation of Micro Simulation Model Output for Mobile Source Air Quality Modeling, in: Road Safety and Simulation International Conference - RSS2013, October 22-25, 2013, Rome, Italy.

Pandian, S., Gokhale, S., Ghoshal, A.K., 2009. Evaluating Effects of Traffic and Vehicle Characteristics on Vehicular Emissions Near Traffic Intersections. Transp. Res. Part D Transp. Environ. 14, 180–196. doi:10.1016/j.trd.2008.12.001

Papson, A., Hartley, S., Kuo, K.-L., 2012. Analysis of Emissions at Congested and Uncongested Intersections with Motor Vehicle Emission Simulation 2010. Transp. Res. Rec. J. Transp. Res. Board 2270, 124–131. doi:10.3141/2270-15

Rakha, H., Dion, F., Sin, H.-G., 2001. Using Global Positioning System Data for Field Evaluation of Energy and Emission Impact of Traffic Flow Improvement Projects: Issues and Proposed Solutions. Transp. Res. Rec. 1768, 210–223. doi:10.3141/1768-25

Salamati, K., Rouphail, N.M., Frey, H.C., Liu, B., Schroeder, B.J., 2015. Simplified method for comparing emissions in roundabouts and at signalized intersections. Transp. Res. Rec. J. Transp. Res. Board 2517, 48–60. doi:10.3141/2517-06

Song, G., Yu, L., Zhang, Y., 2012. Applicability of Traffic Microsimulation Models in Vehicle Emissions Estimates: Case Study of VISSIM. Transp. Res. Rec. J. Transp. Res. Board 2270, 132–141. doi:10.3141/2270-16

Tao, F., Shi, Q., Yu, L., 2011. Evaluation of Effectiveness of Coordinated Signal Control in Reducing Vehicle Emissions During Peak Hours Versus Nonpeak Hours. Transp. Res. Rec. J. Transp. Res. Board 2233, 45–52.

Tong, H.Y., Hung, W.T., Cheung, C.S., 2000. On-road Motor Vehicle Emissions and Fuel Consumption in Urban Driving Conditions. J. Air Waste Manage. Assoc. 50, 543–554. doi:10.1080/10473289.2000.10464041

Unal, A., Frey, H.C., Rouphail, N.M., 2004. Quantification of Highway Vehicle Emissions Hot Spots Based Upon On-board Measurements. J. Air Waste Manag. Assoc. 54, 130–140. doi:10.1080/10473289.2004.10470888

Unal, A., Rouphail, N.M., Frey, H.C., 2003. Effect of arterial signalization and level of service on measured vehicle emissions. Transp. Res. Rec. J. Transp. Res. Board 1842, 47–56.

Várhelyi, A., 2002. The Effects of Small Roundabouts on Emissions and Fuel Consumption: A Case Study. Transp. Res. Part D Transp. Environ. 7, 65–71. doi:10.1016/S1361-9209(01)00011-6

Vasconcelos, L., Bastos Silva, A., Seco, A.M., Fernandes, P., Coelho, M., 2014. Turbo Roundabouts: Multicriteria Assessment on Intersection Capacity, Safety, and Emissions, in: 93rd Annual Meeting of the Transportation Research Board. Washington D.C.

Weiss, M., Bonnel, P., Hummel, R., Manfredi, U., Colombo, R., Lanappe, G., Le Lijour, P., Sculati, M., 2011. Analyzing On-road Emissions of Light-Duty Vehicles With Portable Emission Measurement Systems (PEMS). European Commission Joint Research Centre Technical Report, EUR 24697 EN.

Ying, W., Qiao, F., Yu, L., 2016. Evaluation of the impact of work zone on vehicular emissions in consideration of roughness profile, in: Transportation Research Board 95th Annual Meeting Compendium of Papers. Washington D.C.

Zuger, P., Porchet, A., Burch, D., 2001. Roundabouts: Fuel Consumption, Emissions of Pollutants, Crossing Times, in: First Swiss Transport Research Conference. Ascona.