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On-road measurement of CO_2 vehicle emissions under alternative forms of intersection control

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Abstract

The environmental impact of road intersection operations, and in particular of alternative types of traffic control, has received increasing attention in recent years as a factor to be considered in addition to efficiency and safety. The purpose of this study is to provide experimental evidence about this issue based on direct measurement of CO_2 emissions produced by a vehicle under traffic signal versus roundabout control. Carbon Dioxide was chosen as specific target of the analysis because of its important contribution to the "greenhouse effect". Using data collected with a Portable Emission Measurement System (PEMS) installed on a test car, a before-and-after analysis was conducted on an intersection where a roundabout has replaced a traffic signal. A total of 396 trips were carried out by two drivers in different traffic conditions and in opposite directions along a designated route. Using statistical methods, the existence of significant differences in CO_2 emissions in relation to the type of intersection control was investigated based on the collected data, also considering the effect of other explanatory variables and focusing in particular on peak traffic conditions. More precisely, the effect of the type of control has been characterized using descriptive statistics and permutation tests applied to the entire data set, while an analysis based on binary logistic regression has been performed with specific reference to trips carried out under peak traffic conditions. The results of these analyses support the conclusion that converting a signal-controlled intersection to a roundabout may lead to a decrease in CO_2 emissions.

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Keywords: Air Quality; Emissions; Intersection Control; Traffic Signal; Roundabout; Portable Emission Measurement System.

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1. Introduction

Pollutant emissions produced by road traffic have a major impact on air quality, and are known to depend on traffic, road and vehicle characteristics, on atmospheric conditions and on driving behavior. Intersections are critical locations in terms of emissions due to the considerable variations in vehicle speeds taking place in their proximity (Pandian et al., 2009). Intersection geometric configuration and type of control are important in determining the pattern of traffic flow interruption and thus the associated vehicular emissions.

Roundabouts are increasingly used worldwide and are often built to replace intersections previously controlled by traffic signals or stop signs. While several studies have shown that roundabouts can improve safety (Brilon, 2016, Saccomanno et al., 2008) and, at least in certain flow ranges, the operational performance compared to other types of intersection control (Federal Highway Administration, 2010), their ability to reduce vehicular emissions and fuel consumption has not been fully demonstrated. Analyses specifically focusing on this issue have often reached opposite conclusions (see, for example, Zuger et al. 2001, Ahn et al. 2009, Chamberlin et al. 2011, Hallmark et al.2011), and therefore it seems valuable to provide additional evidence regarding the comparative environmental performance of roundabouts versus other types of intersections.

This study, starting from the results of previous work by some of the authors (Meneguzzer et al. 2017), investigates the environmental effects of replacing a signal-controlled intersection with a roundabout using a before-and-after approach based on field measurements of vehicular emissions. Our analysis focuses specifically on emissions of CO_2, which is considered particularly important because of its contribution to the “greenhouse effect”.

The contribution of this study is twofold. First, the impact of the type of intersection on CO_2 pollution produced by vehicles is investigated carrying out a before-and-after field study on a real intersection rather than adopting simulation models, frequently used in previous studies on the subject. Second, in the statistical analysis of the differences in vehicular emissions, we propose the use of a non-parametric method (two-sample bi-aspect permutation tests) that allows to detect simultaneously differences in location and variability characteristics of the distributions of the observations for the two forms of control and that, to the best of our knowledge, has not been employed so far in this research field.

The paper is organized as follows. Section 2 summarizes previous studies on the effect of different types of intersection control on vehicular emissions. Section 3 describes the study site, the characteristics of the test vehicle and equipment, and the methods used for data collection and treatment. Section 4 reports the results of the statistical analyses carried out in order to compare emissions under traffic signal versus roundabout control. Conclusions and possible future developments of the research are presented in Section 5.

2. Previous works

Previous works analyzing the environmental effects of the type of traffic control of road intersections have adopted most frequently a modeling approach combining traffic micro-simulation and vehicular emission models. On the contrary, only a few experimental studies based on direct field measurement of emission data can be found in the literature.

Zuger et al. (2001) used an instrumented vehicle to carry out a before-and-after study on five intersections that had been converted to roundabouts, and concluded that the effect of the type of control on emissions depended on local conditions and time of day. However, a tendency of roundabouts to perform better than signalized intersections and worse than unsignalized intersections was observed in their study.

Mandavilli et al. (2008) used the aaSIDRA 2.0 software to analyze 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 after roundabout installation. Similar results were reported by Vlahos et al. (2008), who studied the conversion of all-way stop-controlled intersections to roundabouts. More recently, Yang et al. (2017) have found that transforming a two-way stop-controlled intersection into a roundabout can reduce vehicle emissions under most traffic volume scenarios.

Ahn et al. (2009) estimated the fuel consumption and emission impacts of a high-speed roundabout in comparison with two-way stop control and signal control using traffic micro-simulation and microscopic emission models, and concluded that the roundabout does not necessarily reduce emission levels compared to the other forms of intersection control. Hallmark et al. (2011) collected on-road pollution data using a vehicle instrumented with a Portable Emission Measurement System (PEMS), and compared the environmental effects of different types of intersections (signal-controlled, four-way stop and roundabout). Based on the analysis of CO_2, CO, NO_X and HC emissions, the authors concluded that roundabouts do not necessarily perform better than the other forms of intersection control. They also suggested that the results varied by type of pollutant, and stressed the effect of driver behavior.

Jackson and Rakha (2012) analyzed 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, and concluded that roundabouts can minimize the emissions of the above pollutants only in certain ranges of approach demands and turn percentages.

Gastaldi et al. (2014) implemented the microsimulation software S-Paramics and instantaneous emission models for NO_X , PM_{10} and total carbon to analyze a real four-leg intersection where a roundabout had replaced a fixed-time traffic signal. Their results indicate 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.

An empirically supported macroscopic method for comparing vehicular emissions at roundabouts and signalized intersections was proposed by Salamati et al. (2015). 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 factors, including demand-to-capacity ratio, signal timing and signal progression characteristics. Results of an application to a real case indicate that roundabouts tend to be less polluting than traffic signals under low demand-to-capacity ratios; however, when demand approaches capacity, signalized intersections with good progression produce lower emissions than roundabouts.

Finally, the environmental impacts of different types of intersection control have also been studied for an entire corridor; for example, Fernandes et al. (2015) analyzed a sequence of roundabouts and found that, at the arterial level, they performed better than traffic signals but worse than stop controls in terms of emissions.

3. Data collection method

Data were collected at a four-leg road intersection where a roundabout has replaced a traffic signal (Fig. 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.

Field runs were carried out with a Fiat Panda Spark-Ignition (SI) bi-fuel (gasoline/natural gas) passenger car complying with Euro 4 emission standards. During the on-road tests the car was fuelled only with commercial gasoline. Second-by-second on-road measurements of vehicle activity and emissions were obtained using a Semtech (Sensors Inc.) PEMS installed on-board the test car. Several studies have shown the effectiveness of PEMS as tools for collecting emission data that are representative of actual and typical vehicle use (see, for example, Frey et al. 2003 and Unal et al. 2004). All parameters of interest were measured with a time resolution of one second. Emissions were measured in hot conditions, after a 45-minute preconditioning period necessary to let PEMS reach all the set-points.

Two data collection campaigns were conducted along Viale Mazzini, an urban corridor located in the city of Vicenza, Italy, before (April 1-3, 2014) and after (April 14-16, 2015) the conversion of a signalized intersection to a roundabout (Fig. 1). In both cases data were collected over three consecutive weekdays (Tuesday to Thursday). Morning and afternoon test sessions were scheduled from 7.00 to 10.30 and from 16.15 to 19.45. Two subjects drove the test vehicle by alternating in one-hour sessions: a 30-year-old man and a 58-year-old woman.

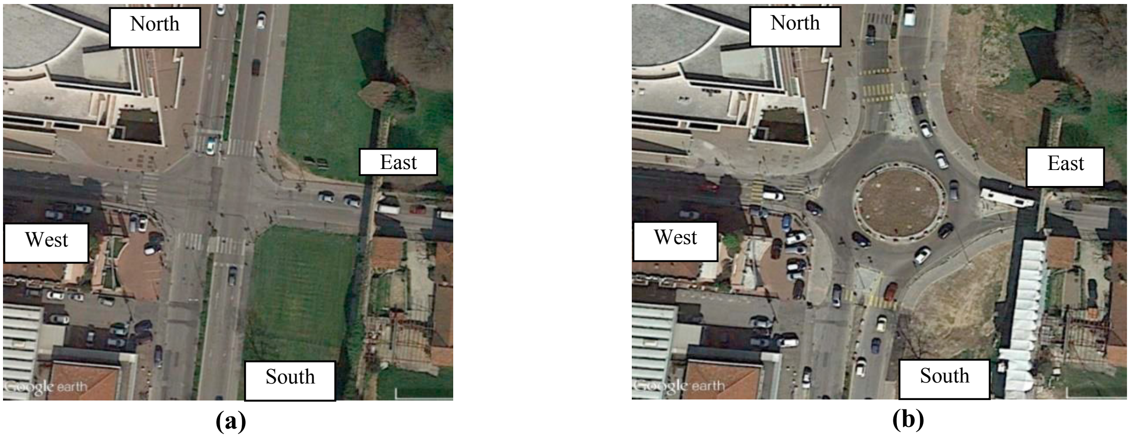
Information on geometric characteristics of the two intersection configurations (Tables 1 and 2) were collected by field observations, and operational conditions were video-recorded during the experimental campaigns. The images were processed extracting the following information for each vehicle:

- 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 temperatures (°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.

In order to isolate the effect of the type of intersection control, vehicular emissions were measured over an influence area that included a 200m-long segment within the test itinerary, consisting of 150m upstream and 50 m downstream the stop/yield line. Test runs were coded as "Trip A" or "Trip B" depending on the direction (North to South or South to North). As shown in Table 3, the dataset was also subdivided based on time of day ("Morning", 7.30-10.00, vs. "Afternoon", 17.00-19.30) and traffic condition ("Peak", 7:30–9:00 and 17.00-19.30, vs. "Off-peak", 9.00-10.00). After aggregation of the instantaneous data, each trip was characterized by information such as speed profile, total travel time and total emissions of various pollutants (among which CO_2 was chosen as the focus of this study). A total of 396 trips were included in the final dataset.



(a) (b)

Fig. 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

Table 3. Dataset of trips used for the analysis.

Trip condition	Signalized Intersection			Roundabout			Total
	Trips [#]	Duration [Mean±SD] [s]	Speed [Mean±SD] [km/h]	Trips [#]	Duration [Mean±SD] [s]	Speed [Mean±SD] [km/h]	Trips [#]
Morning/Off-peak/Trip B	24	48.4±20.1	16.7±8.9	28	38.5±10.3	18.1±4.5	52
Afternoon/Peak/Trip A	43	38.2±22.9	25.4±14.6	31	31.6±6.3	21.8±3.7	74
Morning/Peak/Trip A	32	42.1±21.6	21.1±11.5	39	37.7±9.8	18.5±3.7	71
Morning/Off-peak/Trip A	25	37.8±20.2	23.4±12.2	27	31.9±4.4	21.1±3.0	52
Afternoon/Peak/Trip B	45	46.7±19.5	17.1±8.7	30	71.0±30.4	11.2±4.8	75
Morning/Peak/Trip B	33	43.5±22.5	19.6±10.2	39	49.3±21.8	15.3±5.7	72

4. Results

The evaluation of the impact on CO_2 emissions of the conversion of intersection control was based on statistical analyses carried out on the data collected at the study site. First, the observations obtained before and after the change of intersection control were characterized by means of descriptive statistics computed for the entire set of trips and for six subsamples defined by time of day, traffic condition and trip direction. Second, the statistical significance of the differences between traffic signal and roundabout controls in terms of location and variability indexes of the respective sample distributions was tested. Third, focusing on trips carried out in peak traffic conditions (representing about 75% of the entire dataset), a binary logistic regression model was estimated in order to quantify the effects of the factors that significantly affect CO_2 emissions, with particular attention to the type of intersection control. Peak traffic conditions are usually considered in the process of intersection design and operational analysis, and this provides a justification for restricting to such conditions the analysis of the relationships quantifying the environmental impact of intersection control. The distinction between the two trip directions was suggested by preliminary observations indicating unbalanced traffic volumes.

4.1. Descriptive statistics for CO_2 emissions

Basic statistics describing CO_2 emissions for the entire data sample are reported in Table 4 for the “before” (signal control) and “after” (roundabout) intersection configurations. The total amount of CO_2 produced by the test vehicle during a single trip represents an elementary observation, and the complete sample consists of 396 such observations (202 for signal control and 194 for roundabout). The indicators used to characterize this sample are mean value, median, standard deviation (SD), interquartile range ($Q_1 – Q_3$) and coefficient of variation (CV). The values shown in Table 4 suggest that emissions of CO_2 are higher, on average, for the signalized intersection than for the roundabout. This difference has later been tested for statistical significance (see subsection 4.2).

Table 4. Descriptive statistics for CO_2 emissions (g) by intersection control type.

	Signalized Intersection	Roundabout	Total
Nr. trips	202	194	396
Mean	59.62	51.75	55.76
SD	19.45	18.91	19.56
Median	59.88	45.46	53.05
(Q1 – Q3)	(44.49 – 76.22)	(38.53 – 60.33)	(40.36 – 69.08)
CV%	32.6	36.5	35.1

A more detailed comparison between the two intersection configurations is provided by the box-plots of Fig. 2, which show the location and variability characteristics of the distributions of CO_2 emissions for traffic signal and roundabout and for six subsamples defined by time of day, traffic condition and trip direction. With the exception of subsample 6 (Afternoon-Peak-Trip B), this analysis confirms that emissions of CO_2 are lower and characterized by less variability as a result of the conversion from signal control to roundabout.

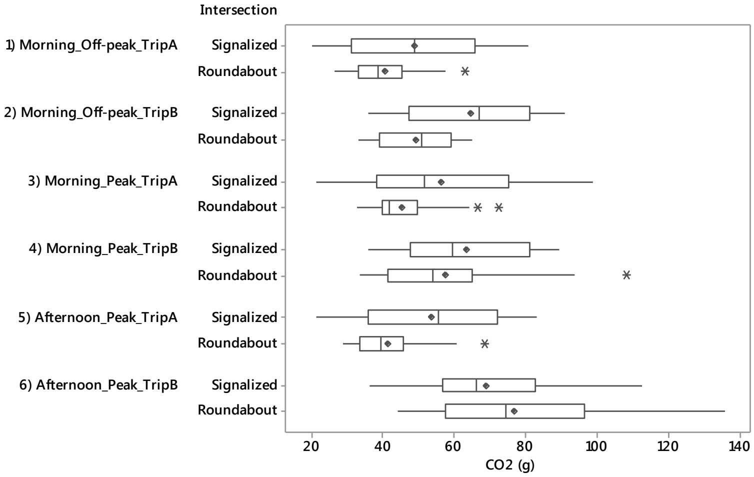


Fig. 2. Box-plots of CO_2 emissions (g) by intersection type and trip conditions.

4.2. Statistical significance of the effects of control type on CO_2 emissions

The next step of the analysis was to determine whether the differences in CO_2 emissions between the two types of intersection are statistically significant. To this end, we applied two-sample bi-aspect permutation tests (Salmaso and Solari, 2005; Pesarin and Salmaso, 2010), which are "distribution-free" statistical procedures that can be used to perform various types of analyses as an alternative to more conventional parametric tests (for example, in place of a Student's *t*-test to determine if two sample means are different at some specified significance level).

In particular, we implemented a *bi-aspect* permutation test, which allows to simultaneously analyze differences in *location* and *variability* of the considered sample distributions. The analysis of the location aspect is based on the comparison of location indexes, while the variability aspect is analyzed based on the comparison of second moments; a solution based on the nonparametric combination of dependent tests theory within the permutation approach is then obtained. In this framework, the global null hypothesis (H_0) that the two groups (the two types of intersection control) have the same underlying distribution may be broken down into two partial null hypotheses, one related to the location aspect and the other related to the variability aspect. Therefore, we first applied two partial permutation tests, one for each partial null hypothesis, followed by their nonparametric combination. The latter makes use of a combining function based on the statistic $-2\sum_i \log(p_i)$, where p_i ($i = 1,\ldots,k$) are the p-values associated with the partial tests, and k is the number of aspects being studied ($k = 2$ in our application). Permutation distributions of partial and combined tests were estimated using a Monte Carlo algorithm based on 10000 independent random permutations of the full dataset. Two-sided alternatives with a significance level $\alpha = 0.05$ were considered for all tests. Bonferroni-Holm's procedure for multiple testing was used in order to keep under control the family-wise Type I error (Pesarin and Salmaso, 2010).

The overall adjusted p-values presented in Table 5 indicate that differences in CO_2 emissions between the two types of control are significant at the 5% level in three out of the six trip profiles obtained by combining time of day (Morning or Afternoon), traffic conditions (Peak or Off-peak) and trip direction (A or B); for one of the remaining trip profiles the p-value lies between 5% and 10%. For all trip profiles the separate tests for location and variability give similar results in terms of significance/non significance of the differences. Considering the overall adjusted p-values that are below the 10% threshold, we observe that emissions of CO_2 are lower for the roundabout than for the signalized intersection.

Table 5. Two-sample bi-aspect permutation tests on emissions of CO2 (g) for signal control and roundabout, with Bonferroni-Holm adjustment for multiple testing.

Trip condition	Signalized Intersection		Roundabout		Test for location, *p*-value	Test for variability, *p*-value	Overall test, *p*-value	Overall adjusted *p*-value
	N. trips	Mean±SD	N. trips	Mean±SD				
Morning/Off-peak/Trip B	24	64.5±16.5	28	49.1±10.6	0.00025	0.00025	0.00025	0.00150
Afternoon/Peak/Trip A	43	53.5±19.5	31	41.3±9.9	0.00265	0.00105	0.00165	0.00825
Morning/Peak/Trip A	32	56.0±21.4	39	45.2±9.9	0.00595	0.00165	0.00305	0.01220
Morning/Off-peak/Trip A	25	48.7±18.9	27	40.3±8.7	0.04275	0.01395	0.02435	0.07305
Afternoon/Peak/Trip B	45	68.8±16.5	30	76.6±23.6	0.09964	0.05964	0.07704	*
Morning/Peak/Trip B	33	63.2±17.0	39	57.2±18.4	*	*	*	*

**p*-value greater than 0.10

4.3. Binary logistic regression model of CO_2 emissions

In order to evaluate quantitatively the associations between CO_2 emission levels, intersection control type and other possibly significant explanatory variables, we developed a logistic regression model based on the subsample of trips carried out during peak traffic conditions (292 observations, approximately equal to 75% of the entire sample). A binary response variable was obtained by classifying each trip into one of two mutually exclusive categories, based on whether or not the emissions of CO_2 exceeded their mean value (equal to 58 g) computed over all 292 trips. Intersection type (IT) and trip direction (TD) were identified as statistically significant predictors; thus, we obtained the following expression of the logistic regression model:

$$\ln\left(\frac{\pi}{1-\pi}\right) = \beta_0 + \beta_1 IT + \beta_2 TD$$

where π represents the probability that the emissions of CO_2 exceed the corresponding mean value, and β_0, β_1, β_2 are the model coefficients, whose numerical values were determined through Maximum Likelihood Estimation.

Table 6 reports the values of the coefficients β_1 and β_2, the corresponding *odds ratios* (equal to $\exp(\beta)$) with the respective 95% Confidence Intervals and p-values, and the Likelihood Ratio Chi-square test with the corresponding p-value. The latter is a test of the null hypothesis that all model coefficients (except β_0) are simultaneously zero versus the alternative hypothesis that at least one of the coefficients is different from zero. The results shown in Table 6 indicate both the overall significance of the model (based on the likelihood ratio test) and the individual significance of each of the two explanatory variables. The values of the odds ratio suggest that emissions of CO_2 per trip are about 2.6 times as likely to exceed 58 g under signal control than with the roundabout, and about 3.8 times as likely to exceed the above threshold for direction B than for direction A. Therefore, trip direction is seen to be a very strong predictor of CO_2 emissions in this case. We hypothesize that this effect, which is specific to the study site under consideration, is mainly attributable to unbalanced traffic volumes and, for the roundabout, also to differences in geometric and functional characteristics between the two directions.

Table 6. Logistic regression model relating risk of "high" CO_2 emissions to intersection type and trip direction.

	N. trips with $CO_2 \geq 58$ g	Total trips	β	Odds Ratio	95% CI	*p*-value
Roundabout	45	139		1		
Signal control	82	153	0.958	2.61	(1.57, 4.32)	0.0002
Trip direction A	41	145		1		
Trip direction B	86	147	1.331	3.78	(2.28, 6.27)	< 0.0001

(Likelihood ratio: χ^2=41.96, DF=2, p-value < 0.0001)

5. Conclusions

This paper has described a field study of vehicular emissions of CO_2 at a road intersection where a roundabout has replaced a traffic signal. The existence of statistically significant differences between CO_2 emissions produced by the test vehicle in the "before" and "after" intersection configurations has been assessed using two-sample bi-aspect permutation tests, a method that can provide more robust evidence as compared to traditional parametric tests, as it allows to detect simultaneously differences in location and variability characteristics of the distributions of the observations in the situations being compared. A significant relationship between CO_2 emission levels, intersection control type and a site-specific variable has then been identified using binary logistic regression.

The main result of the above analyses is that vehicular emissions of CO_2 are lower for the roundabout than for the signal-controlled intersection when the differences are statistically significant. We also found that specific geometric, functional and traffic characteristics of the study site may have a very strong impact on CO_2 emissions.

The research described in this paper can be extended in several directions. An issue of primary interest is the effect on CO_2 emissions of the composition of trips in terms of vehicle operating modes (idle, acceleration, cruise and deceleration) in relation to the type of intersection control. Other aspects that could be explored are the effects on emissions of driving style and, for the roundabout, of conflicting pedestrian flows on intersection crosswalks.

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