ASSESSMENT OF CORRIDORS WITH DIFFERENT TYPES OF INTERSECTIONS: AN ENVIRONMENTAL AND TRAFFIC PERFORMANCE ANALYSIS

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ABSTRACT

Recently, roundabouts in a series have been installed along corridors in order to enhance road safety. However, the benefits of such traffic calming technique on traffic performance and pollutant emissions when compared to other forms of intersections, such as traffic lights and stop-controlled solutions, are not properly known.

This study was focused on using a microscopic approach to evaluate the effects of a corridor with four roundabouts on traffic performance and emissions, in comparison to traffic lights and stop-controlled solutions. Average travel time and number of vehicle stops were used as measures of traffic performance while carbon dioxide (CO₂), monoxide carbon (CO), nitrogen oxides (NOₓ), hydrocarbons (HC) and particulate matter (PM) were used to quantify emissions. The traffic and emissions performance of each solution was evaluated in terms of: a) arterial-level; b) intersection-level; and c) morning peak vs. evening peak periods.

It was found that, regardless of the time period, traffic lights in corridors at the arterial-level produced higher total emissions (>6%), while stop-controlled intersections produced lower emissions (≈12%) compared to roundabouts, mainly due to the fact of unbalanced traffic flows between main and minor roads. Concerning traffic performance, the results showed that there were advantages on implementing roundabouts when the main concern was the number of vehicle stops. At the intersection-level, an emissions improvement (2-14%) was observed for the traffic lights on four-leg intersections.

Keywords: Corridors, Intersections, Roundabouts, Traffic lights, Traffic Performance, Emissions.
1. INTRODUCTION AND OBJECTIVES

The number of roundabouts constructed worldwide has grown faster in the past years. As a result, some local authorities have recently approved and constructed the use of a series of roundabouts in corridors, rather than the traditional solution of coordinated traffic lights. The renewed interest in their implementation can be attributed to the improved safety features of roundabouts that allow reducing vehicle’s speed (1).

Nevertheless, quantitative and qualitative information on the environmental performance of a set of functionally interdependent roundabouts on corridors is lacking (2). A typical question concerning the use of corridors with roundabouts is how traffic will perform. The main goal along a corridor with traffic lights is to coordinate them to assure a good progression so that vehicles can travel through the arterial with a minimum number of stops (1). A series of roundabouts forces all vehicles to slow down at every roundabout, causing several acceleration/deceleration cycles and, as consequence, higher emissions and greater fuel consumption. This is particularly true in downstream areas (3).

Extensive research has dealt with how isolated roundabouts compare to all-way stop control, two-way stop control, and traffic lights in the field of energy and emissions, but the results are not consensual about their benefits. Some studies showed that roundabouts achieved higher emissions and fuel consumption than two-way stop control intersections (4) or traffic lights (5). In contrast, other authors suggested that the environmental and energy performances of roundabouts were largely dependent on traffic flows depending on the approaches and turning demands. Coelho et al. (6) confirmed that fixed-cycle traffic lights caused more emissions than a roundabout (considering a conflict flow of 750 vehicles per hour (vph)) for higher traffic flows. Vlahos et al. (7) explain that when comparing to a traffic signal, the roundabout performed environmentally better with traffic flow compared to all of their approaches by 2,300 vph. Jackson and Rakha (8) demonstrated that roundabouts recorded less fuel consumption and carbon dioxide \((\text{CO}_2)\) emissions than all-way stop control, two-way stop control, and traffic lights when left turn demands were below 30%. Rakha et al. (9) indicated that both single-lane and two-lane roundabouts outperformed the one-way stop-controlled intersection in a three-way intersection in terms of carbon monoxide \((\text{CO})\) emissions and delay. However, one-way stop-controlled intersections were associated with less hydrocarbons \((\text{HC})\), nitrogen oxides \((\text{NO}_x)\) and \(\text{CO}_2\) emissions. Anya et al. (10) investigated the benefits posed by a conversion of a signalized intersection to a two-lane roundabout. They concluded that the reduction in emissions was only relevant, at the intersection-level, in the right turn movements from the minor to the main road. Just recently, Gastaldi et al. (11) found that the environmental benefits of a four-leg roundabout, in comparison to fixed-time traffic signal, were smaller than its operational performance.

In the context of corridors, several researchers have investigated and developed algorithms for signalized arterials to minimize emissions and fuel consumption (12, 13). The few studies carried out in corridors with roundabouts raised some uncertainties about their effectiveness. Hallmark et al. (14) recorded marginal benefits in improved traffic flow of roundabouts within signalized corridors over stop and signal-controlled intersections. In another study, Hallmark et al. (15) compared on-road emission impacts of roundabouts composed to a stop intersection with roundabouts composed by observing signal-controlled intersections along two corridors. The findings suggested that, under uncongested conditions, roundabouts did not perform better than four-way or signal-controlled intersections in the same corridor. Nonetheless, each studied corridor (14, 15) only contained one roundabout throughout its length (roundabouts series were not considered). Krogscheepers and Watters (16) assessed the average speeds, delay, and travel time of six roundabouts along a rural corridor in South Africa and compared that
time with fixed-cycle traffic lights. The authors concluded that roundabouts offered operational advantages over traffic lights, but they recognized that roundabouts became inefficient when the levels of demand increased. More recently, a study conducted with 58 US roundabout corridors developed a methodology for estimating travel speed and Level of Service (LOS) (2). Although these studies developed a very good traffic analysis, they have characteristics in common since they exclude an analysis of the emission impacts (2, 16).

Considering the foregoing discussion, the main motivation for this study can be outlined in two main points. First, there is a need for a suitable methodology capable to estimate the emissions impacts from a series of roundabouts along corridors. Second, although there is an extensive knowledge for traffic operations at isolated roundabouts rather than in sequence, there is a lack of studies comparing the benefits of corridors with different intersection types in the field of emissions. There is a concern that under specific traffic conditions (which are associated with the variability of traffic during the day and geometric features of the roundabouts), the operational and environmental benefits may be lower than expected.

The principal objective of this paper is to compare the traffic performance and emissions of a roundabout corridor to an equivalent corridor where roundabouts are replaced by traffic lights and stop-controlled intersections by using a microsimulation approach to evaluate scenarios in different analysis levels (arterial and intersection levels) and time periods (morning and evening peak periods). To analyze such impacts, a proposed approach that integrated a microscopic traffic model (VISSIM) and emissions methodologies (Vehicle Specific Power – VSP and EMEP/EEA) was used. A genetic algorithm (GA) was used to optimize the traffic signal timing at arterials on emissions.

The novelty of this research in comparison to others studies, taken at roundabout corridors (2, 16) and corridors composed of a roundabout with other intersection forms therein (14, 15), is that it compares both traffic performance and emissions among different corridors layouts. This paper uses an integrated methodology based on a microscopic simulation approach from vehicle activity and traffic flows data simultaneously and intends to focus on the following research questions:

- How do vehicular traffic performance and emissions vary during morning and evening peak hours for corridors with roundabouts and other intersection forms?
- How do design features of the corridor affect the spatial distribution of emissions?

2. METHODOLOGY

The main goal of the proposed methodology is to develop a microscopic simulation platform on traffic and emissions (Figure 1). This platform enables the impacts of capacity and emissions to be evaluated in regards to corridors with roundabouts, traffic lights, and stop-controlled intersections. Figure 1 also depicts the basic structure of the GA-based traffic signal optimizer used in this research. The following sections present a detailed description of the methodological steps.
Figure 1 Summary of methodological steps.

Legend: SPSA - Simultaneous Perturbation Stochastic Approximation; LDV - Light Duty vehicle; HDV - Heavy Duty Vehicles; CO$_2$ - carbon dioxide; CO - carbon monoxide; NO$_X$ - nitrogen oxides; HC – hydrocarbons; PM - particulate matter; GA - Genetic algorithm; O/D - Origin/Destination.
2.1. Data collection

An urban corridor with four single-lane roundabouts, exhibiting high traffic flows, was sought out for this research. The free-flow speed was fairly constant along this corridor, and the spacing was approximately equal between adjacent roundabouts (the coefficient of variability of average spacing was 0.10). The corridor is approximately 1,466 meters (4,810 ft.) long, and it includes two roundabouts with four legs (RBT1 and RBT3) and two roundabouts with three legs (RBT2 and RBT4). The posted speeds on the approach legs are ≥30 km/h. Figure 2 and Table 1 summarize the information regarding the site’s characteristics.

During typical weekdays, traffic counts suggest that morning and evening peak periods occur between 7:00-9:00 a.m. and 4:00-6:00 p.m., respectively. Thus, the following data was collected at the selected corridor for the latter time periods in April 2014:

- Traffic flow (Light Duty Vehicles – LDV, transit buses and Heavy Duty Vehicles – HDV);
- Time-Dependent Origin/Destination (O/D) matrices;
- Gap acceptance data;
Vehicle activity data (speed, acceleration/deceleration and grade).

Traffic and time-dependent O/D matrices were gathered from overhead videos installed at strategic points of the roundabouts. The traffic data was recorded at morning and evening periods over 6 different typical weekdays (Wednesday and Thursday) during three weeks under dry weather conditions. Later, in the transportation laboratory, the traffic data for each vehicle class was compiled to define O/D matrices based on trips along the whole corridor for each vehicle class. Time-gap distributions data (gap-acceptance and gap-rejection) were also extracted from the videotapes.

For vehicle activity estimation, second-by-second vehicle dynamics data was recorded. LDV and HDV, equipped with a GPS Travel recorder, were used to perform several movements along the corridor. 200 GPS travel runs for each movement were extracted and identified for this research (approximately 400 km of road coverage over the course of 8 hours).

### Table 1 Key characteristics of the selected corridor

<table>
<thead>
<tr>
<th>ID</th>
<th>Entry speed</th>
<th>Central Island Ratio</th>
<th>Circulating Width</th>
<th>Distance from upstream roundabout</th>
<th>Average roundabout spacing</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North-South [km/h (mph)]</td>
<td>South-North [km/h (mph)]</td>
<td>[m (ft.)]</td>
<td>[m (ft.)]</td>
<td>[m (ft.)]</td>
<td>[m (ft.)]</td>
</tr>
<tr>
<td>RBT1</td>
<td>29.4 (18.3)</td>
<td>24.7 (15.3)</td>
<td>25 (82)</td>
<td>7 (23)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RBT2</td>
<td>21.3 (13.2)</td>
<td>30.2 (18.8)</td>
<td>24 (79)</td>
<td>8 (26)</td>
<td>304 (997)</td>
<td>304 (997)</td>
</tr>
<tr>
<td>RBT3</td>
<td>27.9 (17.3)</td>
<td>26.1 (16.2)</td>
<td>23 (75)</td>
<td>7 (23)</td>
<td>275 (902)</td>
<td>275 (902)</td>
</tr>
<tr>
<td>RBT4</td>
<td>27.5 (17.1)</td>
<td>26.8 (16.7)</td>
<td>28 (92)</td>
<td>7 (23)</td>
<td>350 (1148)</td>
<td>350 (1148)</td>
</tr>
</tbody>
</table>

**Notes:** CV – Coefficient of Variability (ratio between standard deviation of average roundabout spacing and average roundabout spacing).

As shown in Table 2, the corridor primarily serves through traffic (northbound and southbound). The average number of vehicles entering each roundabout was approximately 1,380 to 1,430 (vph) for the morning and evening peak hours, respectively. Also, the corridor is characterized by high demand of HDV, ranging from 9% to 14%. It was perceived that the traffic data between adjacent roundabouts was relatively similar along the corridor in both the morning and evening peak periods. Nevertheless, the corridor had spare capacity in both time periods. All roundabouts had a critical movement volume-to-capacity ratio (v/c) of 0.85 or less.
Table 2 Average volume observations (LDV and HDV) at data collection corridor during morning and evening peak hours

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning (8-9 a.m.)</td>
<td>RBT1</td>
<td>469</td>
<td>598</td>
<td>265</td>
<td>279</td>
<td>10.3%</td>
<td>970</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>RBT2</td>
<td>505</td>
<td>712</td>
<td>120</td>
<td>-</td>
<td>12.5%</td>
<td>1,103</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>RBT3</td>
<td>477</td>
<td>624</td>
<td>79</td>
<td>121</td>
<td>12.8%</td>
<td>1,189</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>RBT4</td>
<td>497</td>
<td>669</td>
<td>-</td>
<td>91</td>
<td>13.6%</td>
<td>1,189</td>
<td>0.77</td>
</tr>
<tr>
<td>Evening (5-6 p.m.)</td>
<td>RBT1</td>
<td>501</td>
<td>590</td>
<td>275</td>
<td>261</td>
<td>9.5%</td>
<td>998</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>RBT2</td>
<td>543</td>
<td>725</td>
<td>105</td>
<td>-</td>
<td>9.7%</td>
<td>1,012</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>RBT3</td>
<td>544</td>
<td>632</td>
<td>90</td>
<td>105</td>
<td>9.4%</td>
<td>1,269</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>RBT4</td>
<td>563</td>
<td>683</td>
<td>-</td>
<td>95</td>
<td>10.1%</td>
<td>1,269</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Legend: N – Northbound; S – Southbound; W – Westbound; E – Eastbound.

Note: Traffic demand in the evening peak is approximately 3% higher than morning peak period.

* Arterial volume between actual roundabout and upstream roundabout (in the south direction);

** Based on preliminary traffic analysis.

2.2. Scenarios

The baseline scenario is the validated model for the morning and evening peak periods (Figure 2). In order to assess traffic performance and emissions of corridors with different series of intersections types, two scenarios were established:

- Scenario 1 (S1): All roundabouts were replaced by traffic lights;
- Scenario 2 (S2): RTB1 and RBT3 were replaced by two-stop control intersections (West and East approaches), and RBT2 and RB4 replaced by one-stop controlled intersection (West and East approaches).

To model traffic lights, separated left and through lanes from main approaches (North and South) were used. Similarly, a "lead-lead" left-turn phase sequence was considered, as shown in Figure 3. The advantages of this phasing option were: (a) drivers react quickly to the leading green arrow indication; and (b) it reduces conflicts between left-turn and through movements on the same approach (17). Furthermore, the safety between conflicting traffic was not affected significantly since the selected corridor has low left turning rates from the main approaches. A yellow time of 3 seconds was assumed in this study.

The emissions and traffic performance of each traffic restriction scenario were evaluated in terms of: a) arterial-level; b) intersection-level; and c) morning vs. evening peak periods. For the sake of consistency with the following study (2), influence areas were defined to conduct the intersection-level analysis. For the purpose of analysis in this paper, the same influence area among scenarios was considered. Average travel time and number of stops were used as measures of traffic performance while CO₂, CO, NOₓ, HC and PM emissions were used as emissions’ measures.
2.3. Modeling platform

2.3.1. Road traffic modelling

The VISSIM microsimulation model (18) is extensively recognized as a powerful tool for corridors with different intersections to perform an operation analysis (14), because it can be calibrated to set faithful representations of the traffic, especially at capacity (19), and faithful emissions' assessments in urban areas (20). VISSIM allows exporting trajectory files that can be used by external emission models.

The simulation model was run for 90 minutes (7:30-9:00 a.m. and 4:30-6:00 p.m.) with the first 30 minutes used for a warm-up period, and data was extracted only for the remaining 60 minutes (8:00-9:00 a.m. and 5:00-6:00 p.m.). Since transit buses represented less than 0.2% of traffic composition, they were excluded from this analysis. Two separate O/D matrixes for LDV and HDV were generated per 15 minutes for periods between 7:30-9:00 a.m. and 4:30-6:00 p.m.

The treatment of the yield areas was made using the Priority Rules tool of the VISSIM model (18). For the purpose of analysis, the same minimum gap time and headway distance in each one of the yield areas was considered. Model consistency of the corridor with roundabouts was focused into two main steps: calibration and validation.

Calibration was made by modifying driver behavior parameters of the traffic model and examining their effect on traffic volumes and speed for each link. The main driver behavior parameters were divided into car-following parameters (average standstill distance and additive and multiple part of safety distance), lane-change parameters, gap acceptance parameters (minimum gap time and headway distance), and simulation resolution (18).

Figure 3 Layout of the intersections with traffic lights (including phasing) and stop-controlled: a) four-legs; b) three-legs.
A procedure based on the SPSA genetic algorithm to optimize the aforementioned model parameters was used. The objective function was based on the minimization of Normalized Root Mean Square (NRMS) (Equation 1). NMRS is defined as the sum over the two calibration periods of the average of the sum over all links of the root square of the normalized differences between observed and estimated parameters (27). The normalization enables the consideration of several performance measures simultaneously, in this case, link volumes and vehicle speed. The calibration procedure is posed as follows:

\[
\text{Min } NRMS = \frac{1}{N} \sum_{i=1}^{T} \left( W \times \sqrt{\sum_{t=1}^{T} \left( \frac{v_i - \bar{v}(\theta_i)}{v_i} \right)^2} + (1-W) \times \sqrt{\sum_{t=1}^{T} \left( \frac{s_i - \bar{s}(\theta_i)}{s_i} \right)^2} \right) \\
\text{Subject to:} \\
\text{Lower bound } \leq \theta \leq \text{Upper bound} \\
\text{Where:} \\
v_i = \text{Observed link volumes for link } i; \\
\bar{v}(\theta_i) = \text{Estimated link volumes for link } i; \\
s_i = \text{Observed speeds for link } i; \\
\bar{s}(\theta_i) = \text{Estimated speeds for link } i; \\
N = \text{Total number of links in the coded network;} \\
T = \text{Total number of time periods } t; \\
W = \text{Weight to assign more or less value to volumes or speeds.} \\
\]

For calibration criteria, the widely accepted practice is to rely on the Geoffrey E. Havers (GEH) statistic for assessing goodness-of-fit. The difference between observed and estimated link volumes should be less than 5% for at least 85% of the coded links (22). Lastly, queue lengths at entry roundabouts were also compared with default and calibrated values.

The model validation was focused on the comparison between estimated and observed volumes, speeds, travel time, and VSP mode distributions for a preliminary number of simulation runs (between 10 and 20, as suggested by Hale (23)). Validation criteria of volumes, speeds, and travel time were undertaken using GEH statistic (22) and root mean squared percentage error (RMSPE) (24). To examine the discrepancy between the estimated and observed VSP mode distributions, the two-sample Kolmogorov–Smirnov test (K–S test) for a 95% confidence level was employed. More information about this validation procedure can be found in (20). About 80% of the data collected was used for calibration, and the remaining data for validation.

2.3.2. Emission modelling

The methodology used to estimate emissions was based in the Vehicle Specific Power (VSP) (25, 26), which is based on regression models and allows characterizing the vehicle activity data on a second-by-second basis. The VSP values are categorized in 14 modes of engine regime and an emission factor for each mode is used to estimate CO₂, CO, NOₓ and HC emissions from Gasoline Passenger Vehicle (GPV) with engine size <1.2l (25-27), Diesel Passenger Vehicle (DPV) <1.6l (27, 28), and Light Diesel Duty Trucks (LDTT) <2.5l (28). VSP has been shown to be a useful explanatory variable for estimating variability in emissions, especially for CO, CO₂ and NOₓ (29, 30). Concerning HDV emissions and PM emissions from all vehicles types, the EMEP/EEA methodology was used (31). This methodology is based on average values of speed, slope, and load factor.
Different emissions’ factors are available depending on the age and engine capacity of each vehicle class and fuel type.

For both methodologies the following distribution fleet composition was considered for LDV (27): 44.7% of GPV, 34.3% of DPV and 21.0% of LDPT. Since the study corridor was located on relatively flat grades (<1%), the effect of that parameter was ignored.

2.3.3. Traffic signal timing optimization

As noted before, the GA-based traffic signal optimizer was applied for optimizing vehicular emissions (CO₂, CO, NOₓ, HC and PM). The GA is a stochastic search technique based on the mechanics of natural selection and evolution (32). The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was adopted in this case (33) (Figure 1). The following paragraph presents the traffic timing plan optimization variables (according to the corridor characteristics) and the corresponding range values:

- Cycle: 40-120 seconds
- Offset between adjacent intersections: 8 to 24 seconds
- Green time at minor streets: Minimum of 10 seconds.

The optimization of the traffic signal timing was performed separately for both peak periods. NSGA-II code includes binary and real number encodings (33). Thus, a binary encoding technique is employed for the NSGA-II coding scheme. Further, NSGA-II interprets individual chromosomes represented in binary strings of 0 and 1, as optimization variables. For cycle length, green times, and offsets, a fraction-based decoding scheme used in the research of Kwak et al. (34) was applied. Before performing the GA operations, the potential traffic signal timing plans are evaluated by running the road traffic and emissions.

NSGA-II uses a tournament selection approach which has shown good performance in the traffic signal timing plan optimization (33). In this step, better traffic signal plans have higher chances of being selected. Then, a crossover operation based on a procedure to compose a mating pool and create a new population for the next generation is performed. After that, a uniform crossover is applied for each pair of chromosomes from the tournament selection in which individual bits are compared between two chosen chromosomes, and the compared bits are replaced with a 0.5 probability. A mutation operator changes single bits of chromosomes when each bit satisfies the mutation probability of 0.03. These probabilities are recognized to be effective for traffic signal timing plan optimization (34).

3. RESULTS AND DISCUSSION

3.1. Model evaluation

Figure 4 exhibits the observed and estimated traffic volumes and vehicle speeds before (with VISSIM default values) and after the calibration of the traffic model for the morning and evening periods. The results confirmed larger improvements for vehicle speeds, while traffic volumes were only slightly modified. After the calibration, the speeds improved for 61% (n=41) and 62% (n=42) of the links in the morning and evening peak periods, respectively, while remaining values kept similar to the initial values. Moreover, R-squared values higher than 0.90 of the estimated parameters, versus observed parameters, were recorded for the calibration procedure.
Table 3 summarizes the traffic calibration and validation results obtained for NRMS and GEH statistics, queue length, and VSP modes distribution. Both lane-change parameters and simulation resolution are unaffected by the calibration. In the first case, all coded links have one lane. In the second case, a value of 10 time steps/(sim.s) was used to fit the two resolution of traffic and emissions models (a second-by-second basis). It was demonstrated that the calibrated model parameters improved the GEH statistic, that is, all the links achieved a GEH statistic less than 5, thereby satisfying the calibration criteria. The NRSM went from 0.47 to 0.29 in the morning peak and 0.45 to 0.28 in the evening peak.

It was also found that default values underestimated speed values, and yielded larger queues at entry areas (>15% than observed data). This means that initially some of the traffic model behavior parameters did not properly represent the specific-site traffic operations, and possibly some of their values were relatively high. This was particularly true in the case of stand-still and headway distance for which their decrease was 60% and 40%, respectively, in relation to the default values. The difference between observed and estimated values of queue lengths (>6% with calibrated values) confirmed the correctness of the above calibrated driver behavior parameters. Similarly, the calibrated minimal gap time was close with those obtained from the field measurements (3.0 s), which reflects Portuguese driving habits (35).

Concerning the validation results (Table 3), the comparison of observed and estimated flows and travel time was conducted using a different data sample from the calibration and an additional 15 random seed runs (22), which showed that more than 85% of the coded links recorded GEH values below 5 and RMSPE below 20%. The analysis of VSP modes distribution indicated that 67% (n=45) and 100% (n=64) of the coded links did not show significant differences at a 95% and 99% confidence level, respectively, considering the evening peak conditions. These validation results suggest a very good degree of consistency for all cases (21, 23). The resulting validation settings were subsequently applied to all scenarios.
Figure 4 Observed vs. Estimated speed and traffic volumes: a) Default parameters for morning peak; b) Calibrated model for morning peak; c) Default parameters for evening peak; d) Calibrated model for evening peak.
### Table 3 Summary of calibration and validation results for the traffic model

<table>
<thead>
<tr>
<th>Period</th>
<th>Model</th>
<th>Parameter</th>
<th>Value</th>
<th>NRMS</th>
<th>GEH</th>
<th>Queue length</th>
<th>VSP Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average standstill distance (m)</td>
<td>2.0</td>
<td>0.469</td>
<td>&lt; 5 for 98% of the cases</td>
<td>≈ 17% higher than field data</td>
<td>50% and 90% of the links not statistically significant at a 95% and 99% CI</td>
</tr>
<tr>
<td></td>
<td>Default</td>
<td>Additive part of safety distance</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple part of safety distance</td>
<td>3.0</td>
<td>0.285</td>
<td>&lt; 5 for 100% of the cases</td>
<td>≈ 7% higher than field data</td>
<td>72% and 100% of the links not statistically significant at a 95% and 99% CI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimal gap time (s)</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimal headway (m)</td>
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<td>70% and 100% of the links not statistically significant at a 95% and 99% CI</td>
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<td>1.5</td>
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<td>&lt; 5 for 100% of the cases</td>
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<td>70% and 100% of the links not statistically significant at a 95% and 99% CI</td>
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**Legend:** CI – Confidence Interval

**Note:** - The weight factor (W) was set to 0.7;
- Validated model with 15 random seed runs.

### 3.2. Traffic performance measures and emission rates

This section compares emissions and traffic performance parameters of the two scenarios to the baseline scenario. The average values of optimizing parameters became stable after 50 generations indicating that NSGA-II converges. Thus, the following parameters were used in the corridor with traffic lights in the morning and evening peak periods, respectively: cycle: 45s and 41s; offset: 19s and 12s; and green time at minor streets: 12s and 10s. The emissions and traffic performance impact results were presented in Table 4.
by analysis-level and scenarios to the period of morning, evening, and aggregate time
periods. Key observations from the data in Table 4 are:

- Considering the overall corridor and morning peak hour, significant differences
  between S1 and Baseline were observed (vehicles produce an average amount of
  additional emissions of 7% in S1); S2 gave lower emissions at the arterial-level
  analysis, mainly in terms of CO$_2$ and HC with reductions of 12%-13%, but is
  ineffective in terms of idling situations (increase of 7% in the number of stops).
- S2 was the best environmental solution in the evening peak period. It had average
  emissions reductions of about 12% and yielded the smallest travel time with 16%.
  Slight differences between the environmental performance of Baseline and S1
  compared to the morning peak conditions;
- For the intersection-level analysis and morning peak conditions, the findings
  pointed out considerable differences among scenarios during the morning peak
  period especially (all pollutants increased between 14% and 19% with S1, while
  the number of stops increased by more than 30%). However, the RBT4/I4 in S1
  performed environmentally better than roundabouts (8-10% depending on the
  pollutant). There were decreases in emissions of about 25% for CO$_2$, CO, and HC
  for the RBT4/I4 in S2;
- By an intersection-level analysis with evening peak conditions, S2 provided a
  significant advantage in traffic operations on four-leg intersections, as compared
  with the alternative of a roundabout (6% and 9% less emissions in RBT1/I1 and
  RBT3/I3, respectively). S1 presented the highest number of vehicle stops and
  emissions’ amounts on those intersections, but average emissions (5-14%)
  depending on the pollutant) and travel time (<6%) decreased at the three-leg
  intersections when compared to roundabouts. S2 achieved significant emissions’
  reduction at the RBT4/I4 (its implementation allowed CO$_2$ and average travel time
to be reduced by 25% and 19%, respectively);
- Considering the aggregate contribution of two time periods, S2 also gave the best
  emissions scenario at the arterial-level analysis (-12% of CO$_2$ in comparison to
  baseline). S1 and Baseline emitted the highest amount of CO$_2$ at the four-leg and
  three-leg intersections, respectively.

In summary, the comparison of the corridors layout dictates different results
between roundabouts and traffic lights. In some situations, S1 and S2 achieved lower
travel time and higher stop-and-go situations, when compared to roundabouts. This point
was explained by the high travel time in minor roads (caused by longer red times and the
obligation to come to a complete stop at the intersection). Similarly, the travel time was
compensated in the main roads since the most of the traffic goes through. Also, vehicles
made left turns from the main roads to the minor roads, previously stopping and waiting
for a gap in opposite through movement. In roundabouts, vehicles do not always perform
complete stops since most of conflicting traffic comes from minor roads. These traffic
performance findings were also found in the research of Krogscheepers and Watters (15).

This research suggests that some segments of the corridor with roundabouts have a
relevant impact on speeds and on the spatial distribution of emissions. Consequently, it is
important to understand how design features of the corridor affect both vehicle dynamics
and emissions. This subject is addressed and discussed in the following section.
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<th>Period/Area</th>
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<th>CO$_2$ (kg)</th>
<th>CO (g)</th>
<th>NOx (g)</th>
<th>HC (g)</th>
<th>PM (g)</th>
<th>Traffic Flows (s/veh)</th>
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Notes: OC: Overall Corridor; 1: Intersection 1 (RBT1/I1area); 2: Intersection 2 (RBT2/I2area); 3: Intersection 3 (RBT3/I3area); 4: Intersection 4 (RBT4/I4area). Maxmimum reduction allowed.
3.3. Spatial distribution of emissions

In order to complete the analysis, speeds and CO\(_2\) emissions’ distributions in each meter segment length were compared along the corridor, considering all intersections, which consisted of roundabouts (baseline), traffic lights (S1), and stop-controlled (S2) (Figure 5). The comparison was conducted in both through movements (North-South and South-North) and time period. The exhibit indicated that the spatial distribution of speeds and CO\(_2\) were highly symmetrical along the selected corridor for all roundabouts. The spacing between adjacent roundabouts and the geometric features were similar for all roundabout layouts. Higher deceleration and acceleration rates were recorded upstream and downstream of the intersections in both directions. Accordingly, sharper variation of the CO\(_2\) curve between the exit and the yield/stop lanes was observed (overall contribution on emissions was approximately 35%, 30% and 34% on baseline, S1, and S2, respectively). When vehicles travelled toward adjacent intersections, they generated higher CO\(_2\) levels after the traffic lights implementation (more than 15%).

![Graphs showing speed and CO\(_2\) distributions along the corridor per scenario: a) Morning peak (North-South); b) Morning peak (South-North); c) Evening peak (North-South); and d) Evening peak (South-North).]
4. CONCLUSIONS

This study explored the effect of an urban corridor with four roundabouts on traffic performance and emissions generated from vehicles. A microscopic traffic model was integrated in conjunction with emission models to assess the consequences of replacing a series of roundabouts in arterials (baseline) by traffic lights (scenario 1) and stop-controlled intersections (scenario 2). The traffic performance and emissions of each solution were compared at the arterial-level, intersection-level, and morning and evening peak periods. These main findings were found at a corridor level:

- Roundabouts led to the lowest number of vehicle stops and were environmentally better than the traffic lights solution (4-5%, depending on the pollutant);
- Traffic lights were the worst solution on both time periods: emissions increased about 7% and 2% compared to roundabout layout in the morning and evening peak periods, respectively; the number of stops increased more than 50%;
- Stop-controlled was the best solution in both time periods in terms of emissions and some mobility measures: 12% less vehicle emissions and nearly 16% less travel time.

The following findings were obtained at an intersection level:

- Roundabouts recorded the lowest number of vehicle stops and less total emissions than traffic lights solution (8-19%, depending on the pollutant) on four-leg intersections;
- For traffic lights, the average total emissions decreased in the evening peak period (2-14%, depending on the pollutant) on three-leg intersections, and there was approximately 2% less travel time on three-leg intersections;
- Stop-controlled led to a decrease in the average total emissions in relation to the roundabout solution (3-24%, depending on the intersection), and travel time was shortened from 6% to 23% (depending on the intersection).

It should also be emphasized that the unbalanced traffic flows between main roads (> 500vph) and minor roads (< 125vph in almost approaches) justified the advantages of the implementation stop-controlled solution on the case study.

The findings of the paper also confirmed that the vehicles that travelled at the mid-block areas toward adjacent traffic lights, drove at higher speeds when compared to adjacent roundabouts, and consequently higher emissions were produced throughout the corridor.

This research highlights the importance of identifying the specific characteristics of a corridor before implementing a specific type of intersection in order to enhance both traffic performance and emission impacts. Moreover, it determines whether there is a need for a corridor-level analysis, an intersection-level analysis, or both.

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