AGENT-BASED MICRO SIMULATION TO ASSESS THE PERFORMANCE OF ROUNDABOUTS CONSIDERING DIFFERENT VARIABLES AND PERFORMANCE INDICATORS

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ABSTRACT

Traffic congestion problems in intersections are usually solved by building infrastructures such as roundabouts. Several variables influence its performance, e.g. geometry, size and driving behaviour. Thus, it becomes necessary to compare these variables. This paper proposes a simulation model, developed to compare the performance of roundabouts, employing the object and agent modelling paradigms of Simio, to model the individual behaviour of vehicles. The results indicate the optimum size of roundabouts is around 40 meters of diameter and that the driving style has a greater influence on the performance of the roundabout than its unbalancing. In addition, it was found that roundabouts considering unbalancing and human behaviour decreased: the flow of vehicles in 8%, the waiting time per vehicle in 3 minutes, the queue size in 90%, the number of stops per vehicle in 88% and vehicles spent three times more fuel, than the roundabouts that did not consider these variables.

Keywords: Roundabout, Micro simulation, Agent modelling, object paradigm, Simio.

1. INTRODUCTION

Since the motor vehicle became the main means of transport, we have been witnessing a growing number of vehicles circulating on traffic lanes, which results in traffic congestion problems. To overcome them, usually the intersection is expanded through the construction of roundabouts. However, there are different geometries and different sizes that can be adopted, configuring several variables that can be parametrized by managers, including the number of lanes. Furthermore, the driving style also affects the performance of roundabouts. Furthermore, these geometric alterations may be limited to the site conditions, such as limited space, which may limit the geometries.

Simulation enables the visualization of the results from modifications made to a system, without making experiments in the real world. However, to the best of the knowledge of the authors, the traffic simulation packages available lack the of modelling not standardized concepts, such as the one hereby proposed. As such, discrete-event simulation was used for this work. From the simulation tools on the market, the choice was Simio, a tool that uses object and agent-oriented paradigms, which are essential for this project, since it becomes possible to model the individual behaviour of each vehicle.

In this sense, the purpose of this paper is to propose a general-purpose discrete simulation model that was developed to assess the performance of roundabouts of different sizes and to analyse the impact of a specific human behaviour on the system. This impact can be felt on several aspects. For instance, roundabouts with low performance result in longer times spent on queues by drivers, bigger traffic queues and even more pollution. Thus, this paper proposes an agent modelling approach to model vehicles travelling to access a roundabout, using Simio, a recently developed object oriented discrete simulation tool that also supports processes and events. The KPI (Key Performance Indicators) include the flow of vehicles, queue size, crossing time and fuel consumed and its gas emissions.

This document is organised in six sections. The main purpose of the next section is to make a review of the literature on discrete-event simulation tools. Section 3 is dedicated to the data gathering and validation process, also offering the required literature background on traffic situations related to roundabouts. In section 4, the simulation model is briefly described and section 5 is related to the simulation experiments conducted. Last section discusses some withdrawn conclusions.

2. LITERATURE REVIEW

Currently there are not many studies that use general-purpose discrete-event simulation models for modelling traffic problems. A possible justification for this is that most of the studies that use simulation in problems related to traffic, use packages of micro simulation tools like VISSIM or AIMSUN. The number of commercial tool options can be very high; thus, simulation tool comparison becomes a very important task.

Hlupic and Paul (1999), compare a simulation tools, distinguishing between users of software for educational purposes and users in industry. In his turn, Hlupic (2000) developed a survey to academic and industrial users on the use of simulation software, to discover how the users are satisfied with the simulation software they

use and how this software could be further improved. In Dias, Pereira and Rodrigues (2007), Pereira, Dias, Vik and Oliveira (2011) and Dias, Vieira, Pereira, and Oliveira (2016) a comparison of tools based on popularity on the internet, scientific publications, WSC (Winter Simulation Conference), social networks and other sources, was established. According to the authors, popularity should not be used as the only comparison indicator, otherwise new tools, better than existing ones, would never get market place. However, a positive correlation may exist between popularity and quality, since the best tools have a higher chance of being more popular. According to this ranking, the most popular tool is Arena, whilst the classification of the "newcomer" Simio is noteworthy. Vieira, Dias, Pereira and Oliveira (2014a) and Oueida, Char, Kadri and Ionescu (2016) compared both tools taking into consideration several factors.

Simio was created in 2007 from the same developers of Arena and is based on intelligent objects (Sturrock and Pegden 2010, Pegden 2007, Pegden and Sturrock 2008). Unlike other object-oriented tools, in Simio there is no need to write programing code, since the process of creating objects is completely graphic. The activity of building an object in Simio is identical to the activity of building a model. In fact, there is no difference between an object and a model (Pegden 2013). A vehicle, a costumer or any other agent of a system are examples of possible objects and, combining several of these, one can represent the components of the system in analysis. In other words, the user can use realistic representations of the objects that compose the real system being modelled and, thereafter, at a lower level, define additional logic to the model, through the development of processes for instance. This way, Simio complements the main object paradigm with other paradigms such as events, processes and agents. Since each entity can execute its own processes and thus make their own decisions, applied to the context of vehicles in a traffic system, the result is a simulation model, on which entities are modelled as agents.

Thus, a Simio model looks like the real system. This fact can be very useful, particularly while presenting the results to someone non-familiar to the concepts of simulation. In Simio the model logic and animation are built in a single step (Pegden and Sturrock 2008, Pegden 2007). This feature is very important, because it makes the modelling process very intuitive. Moreover, the animation can also be useful to reflect the changing state of the object. In addition to the usual 2D animation, Simio also supports 3D animation as a natural part of the modelling process. To switch between 2D and 3D views the user only needs to press the 2 and 3 keys of the keyboard. Moreover, Simio provides a direct link to Google Warehouse, a library of graphic symbols for animating 3D objects. Next section complements the literature review of this paper, by providing a review over literature focusing on traffic situations related to roundabouts.

3. DATA GATHERING AND VALIDATION

To build a model capable of representing the real system, the following data related traffic situations was gathered through literature collected and analysed:

- **Safety distances kept while driving:** Drivers that travel at a speed next to 50 km/h maintain a safety distance of about 16 meters Luo, Xun, Cao and Huang (2011).
- **Space occupied by a vehicle in a queue:** The analysed studies indicate that a stopped vehicle occupies a distance between 7.6 meters and 7.9 meters (Bonneson 1992, Messer and Fambro 1997, Zhu 2008, Herman, Lam, Rothery 1971).
- **Start-up acceleration:** Zhu (2008) analysed several studies regarding this matter. The author developed a polynomial acceleration model characterized by expression 1. Since in Simio it is not possible to implement the acceleration of entities, it was necessary to use the correspondent velocity expression 2. In addition, we have replaced t with $t-1$.

$$a = 2{,}46 - 0{,}24t + 0{,}006t^2 \qquad (1)$$

$$v = 2{,}66 + 2{,}46t - 0{,}12t^2 + 0{,}002t^3 \qquad (2)$$

- **Reaction time of drivers on roundabouts:** It is difficult to find in the literature and to measure in the filed the reaction time that drivers take to start accelerating, from a resting position, in a roundabout queue. This is because drivers are constantly trying to access a gap in the roundabout and many times they do not completely stop, which influences their start-up accelerating process. This does not happen, for instance, in signalized intersection, since drivers must wait for a red light that they do not know when it is going to change. Thus, the reaction time of drivers in the queues of signalized intersection was used. According to Bonneson (1992), the first vehicle of a queue takes 1 to 1.3 seconds. On the remaining positions of a queue, drivers take 2 seconds (Bonneson 1992, Messer and Fambro 1997), or1.5 to 2 seconds (Bonneson 1992, George and Heroy 1966).

These values were incorporated in Simio, adjusting them to have the reaction time of drivers being dependent on their distance to the one on the first position of the queue, as authors agree. Moreover, since the reaction time of drivers in roundabouts in lower than on signalized intersections, these values were calibrated. Figure 1 shows the reaction time of two samples of drivers from a modelled roundabout and a signalized intersection, in Simio.
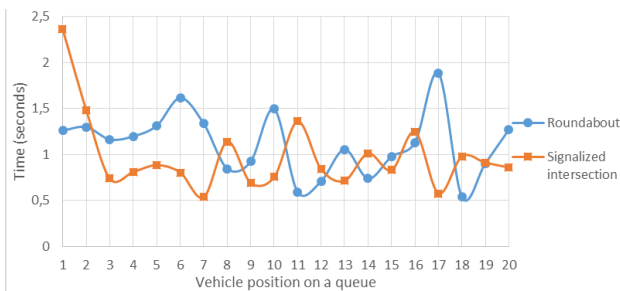
Figure 1: Average reaction time of drivers

As can be seen, the first vehicle of the queue on the signalized intersection took considerable more time than the vehicle on the same position of the queue of the roundabout. Concerning the reaction time of the vehicles on the remaining positions, their values decrease until an average of 1 second. After that, the average value is maintained.

- **Velocity while circulating inside the roundabout:** Skrodenis, Vingrys and Pashkevich, (2011) stated that speeds of vehicles, circulating inside roundabouts, of diameter varying between 16 to 45 meters, should be around 16-30 km/h. Furthermore, the speed of vehicles entering and circulating roundabouts tends to be higher for bigger roundabouts (Brilon 2005). Based on this and on numerous calibrations to the simulation model, it was considered that the vehicles could accelerate to a maximum speed of 30 km/h in roundabouts of similar size. For smaller roundabouts, the vehicles will only be able to speed up until 25 km/h. While circulating on roundabouts of 60 meters of diameter the vehicles will be able to speed up until 35 km/h and on roundabouts of 80 meters the vehicles will be able to speed up until 40 km/h. Thus, these speed differences also have an influence on the space gap required by the drivers to access the roundabouts of different sizes.
- **Space gap to access the roundabout:** While circulating a roundabout, the velocity of a vehicle affects the required space, or time, for a second vehicle to access the same roundabout. Since these values were modelled based on data collected from the literature, the authors empirically calibrated the required space gap, to minimize the occasions on which a vehicle decides to access a roundabout and, because of that, another vehicle, circulating on the roundabout, had to slowdown, since the available gap was too small for the other vehicle to access the roundabout. Thus, the space required for a vehicle, to access the roundabout was 17 meters for the roundabout of around 10 meters of radius, 22 meters for the roundabout with around 20 meters of radius, 33 meters for the roundabout of a

radius of around 30 meters and 47 meters for the roundabout with around 40 meters of radius.

- **Instant speed when crossing the stop line of an intersection:** Bonneson (1992) stated that the velocity of each vehicle increases until the fourth or fifth vehicle. From that number, the velocity of the vehicles tends to stabilize.
- **Fuel consumption and emission rates:** Some of the models that estimate consumption rates and emissions include those based on the instant velocity of vehicles. Tong, Hung and Cheung (2000) established a formula for the fuel consumption of diesel vehicles in order of the instantaneous vehicle speed, whilst Chan et al. (2004) used a formula to estimate "the fuel consumption of petrol vehicles as a function of the instantaneous vehicle speed". Notwithstanding, there are models that consider other factors, such as the model proposed by Akçelik and Besley (2003), which considers the acceleration of the vehicle, its mass, instant speed, among other parameters. Akçelik (1983) also provided a model that expresses fuel consumption as a function of cruising, idling and stop-start manoeuvers. In its turn, Guo and Zhang (2014) indicated the formula currently being used by some traffic micro simulation tools (c.f. VISSIM, TRANSYT, and SYNCHRO).

Apart from formulas that estimate the consumption and emission rates, Coelho, Farias and Rouphail (2006) presented the emission factor of HC, NOx, CO2 and CO for several vehicle speed powers. In its turn, Tong, Hung and Cheung (2000) collected data related to vehicle speed, emission, and fuel consumption from four types of vehicles while they travel on different driving modes (i.e., idle, acceleration, cruise and deceleration). The authors presented the results in g/km, g/sec and g/kg fuel. Even though, there are more recent works that provide similar data, like the one Lau, Hung and Cheung (2011) conducted. These authors studied the CO, NO and HC emission rates, as well as the fuel consumption rates from four LPG taxis of different years, driven under urban traffic conditions. Notwithstanding, the data used in this study was the one collected by Tong, Hung and Cheung (2000), since it considers the time the drivers spend on each of the four driving modes. Thus, is consists on a simple, yet efficient, way to model the main consume patterns. The data provided by the authors and used on this study is presented in Table 1. To the best of the knowledge of the authors, this reference was the only one meeting the previously stated established requirements. Nowadays, all these values should be inferior, albeit at the same proportion.

Table 1 Modal emission and fuel consumption rates (Tong, Hung and Cheung 2000)

	Driving mode	Modal emission rate (mg/sec)			Fuel Consumption
		CO	HC	NOx	
Passenger Car	Acceleration	9.54	0.69	0.62	62.62
	Cruising	9.15	0.49	0.77	39.1
	Deceleration	9.96	0.58	0.69	28.11
	Idling	2.99	0.36	0.14	18.11
Petrol Van	Acceleration	15.14	1.85	1.96	67.29
	Cruising	14.52	1.70	1.81	52.14
	Deceleration	17.30	1.91	2.33	52.16
	Idling	8.39	1.88	0.81	12.71
Diesel Van	Acceleration	2.71	0.65	0.91	62.02
	Cruising	2.64	0.54	0.79	52.47
	Deceleration	2.67	0.65	0.89	56.01
	Idling	1.33	0.22	0.44	18.52

4. MODEL DEVELOPMENT

To enhance the animation of the simulation model, 3D models of road segments, vehicles and others were downloaded from Google Warehouse. Some sample videos of the model in execution were recorded and can be watched online at the following address: http://pessoais.dps.uminho.pt/lsd/pre_semaforos/. Figure 2 shows the modelled roundabout.
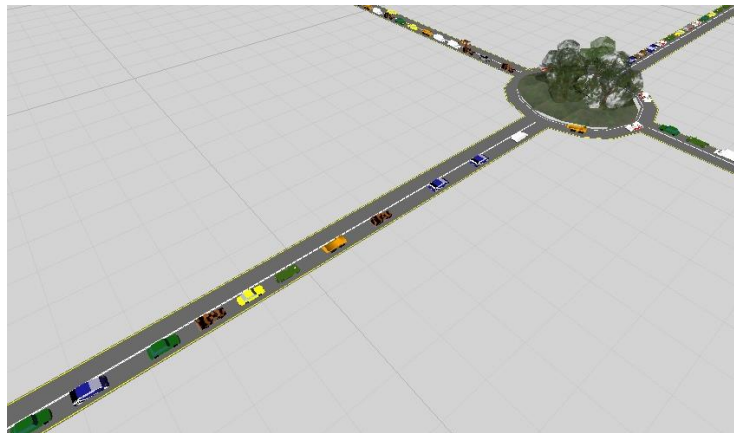

Figure 2: 3D view of the modelled roundabout

To model the behaviour of the vehicles on roundabouts, it was necessary to create many processes, functions, states among others, on the Simio software, to model all the traffic situations. Nonetheless, in this paper, only some of the processes will be illustrated. Figure 3 shows the process developed to have vehicles maintaining a safety distance between the vehicles of the model, while they are traveling. Figure 4 shows the process responsible for updating the fuel and emissions rates of the vehicles. To accurately calculate these rates, the 4 distinct operating modes of the vehicles (i.e. idle, acceleration, cruise and deceleration) had to be correctly defined.
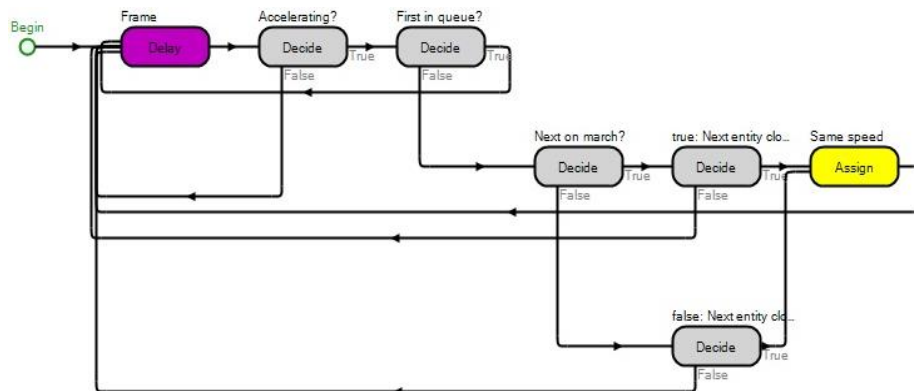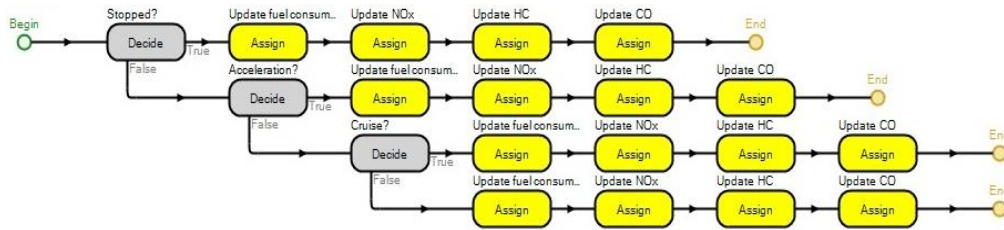

Figure 3: Process MaintainSafeDistance

Figure 4: Process UpdateConsumption

The destination that the vehicles chose affects the system. The reason for this is that, in this type of intersection, all the vehicles compete for a gap to access the roundabout. Thus, when a vehicle arrives at the roundabout it decides whether it enters the roundabout or not, by evaluating the available gaps. While these times and distances are subjective to each driver, they are also influenced by the speed of the vehicles traveling in the roundabout and of the vehicle trying to enter it. Thus, in the developed simulation model, the speed of the vehicles approaching the entry lanes of the roundabout, and of the ones circulating inside the roundabout, is adjusted according to the size of the roundabout. The process that models the behaviour of each driver when evaluating if there is enough space in the roundabout to enter it is represented in Figure 5. In this process, each entity is actively deciding – agent modelling - if it can enter or not the roundabout, by analysing the distance to the closest cars at his left, on the roundabout.
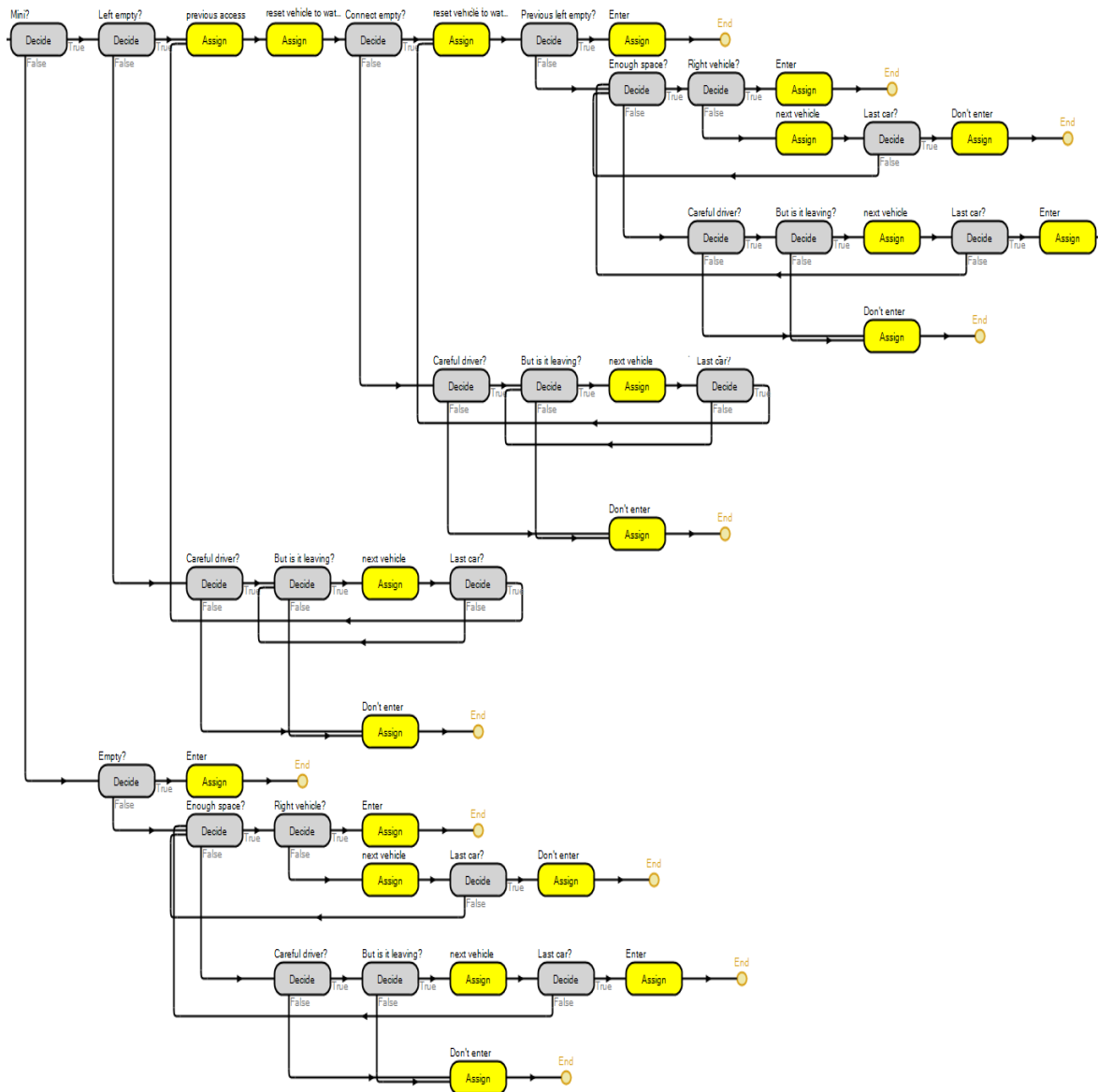

Figure 5: Agent process: "EnterOrNotTheRoundabout"

5. SIMULATION EXPERIMENTS

For the present work, the authors considered the following properties, or parameters, for the conducted simulation experiments:

- the frequency with which the vehicles arrive to the system,
- the radius of the roundabout,
- the balancing of the roundabout, i.e., how balanced the outflow rates are, on the accesses of the roundabouts;
- the driver behaviour.

As KPI (Key Performance Indicators), the following were defined: average crossing time per vehicle in seconds, the average number of vehicles on the queues, the average flow of vehicles in vehicles/hour, the average total fuel consumed per vehicle in milligrams, the average total emissions of vehicles in milligrams (CO, HC and NOx) and the average number of stops per vehicle. Moreover, the values 4, 8, 13 and 50 seconds were considered, respectively, for the time interval that defines the creation of vehicles, and therefore the intensities very high, high, medium and low. Based on previous results (Vieira, Dias, Pereira and Oliveira 2014b), a warm-period of 360 seconds was used, along with a simulation time of 2 hours and 6 replications. Regarding these KPI, the following was considered:

- The time to cross an intersection is the elapsed time between when a vehicle is created and when it travels of 150 meters after having crossed the intersection.
- The number of vehicles on a queue is measured on every minute.
- The flow of vehicles is the inverse of the time interval between passages of vehicles through the intersection.
- The fuel consumption and its emissions rates start being accounted when vehicles are created and are updated every minute, until vehicles crosses the intersection.
- The average number of stops per vehicle recorded when one enters the roundabout.

The values considered for the radius of the central islands of the roundabouts were 10, 20, 30, 40 and 50 meters. Table 2 shows the obtained results.

Table 2: Comparing the modelled roundabouts

Traffic intensities	Very high				High				Medium				Low			
Radius (meters)	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
Flow rates (vehicles/hour)	1 537	1 974	1 766	1 636	1 525	1 799	1 752	1 595	1 108	1 109	1 108	1 108	289	289	289	289
Crossing time (minutes)	10,3	7,7	8,6	9,3	8,1	1,3	3,2	6,0	1,1	1,1	1,1	1,2	1,1	1,1	1,1	1,1
Queue size (number of vehicles)	66,0	61,5	62,1	61,8	51,2	1,9	16,9	37,0	0,3	0,1	0,2	0,4	0,1	0,0	0,0	0,0
Total fuel consumed per vehicle (g)	18,46	14,82	15,55	16,00	14,74	3,17	6,40	10,79	2,68	2,66	2,80	2,95	2,59	2,63	2,71	2,77
Total CO emissions per vehicle (g)	2,98	2,41	2,54	2,63	2,43	0,68	1,17	1,85	0,60	0,60	0,63	0,66	0,59	0,60	0,62	0,64
Total HC emissions per vehicle (g)	0,28	0,21	0,23	0,24	0,22	0,04	0,09	0,16	0,03	0,03	0,04	0,04	0,03	0,03	0,03	0,04
Total NOx emissions per vehicle (g)	0,17	0,14	0,15	0,15	0,14	0,05	0,08	0,11	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
Number of stops	34,3	29,4	28,8	27,1	26,9	1,7	9,5	17,6	0,6	0,3	0,5	0,6	0,3	0,2	0,2	0,1

As can be seen, in low and medium traffic intensities, regardless of the size, roundabout behaved similarly for all KPI. Yet, when traffic intensities increase (high or very high), the obtained results indicate that the roundabout performed better for radius of 20 meters, which is in accordance to previous studies (Oketch, Delsey and Robertson 2004). This can be explained by the more moderate speeds of the vehicles traveling in smaller roundabouts. Thus, the space gap for vehicles trying to enter the roundabout increases, conversely to bigger roundabouts, where vehicles, circulate at higher speeds and the space gap required also increases, as was also stated by previous studies (Fouladvand, Sadjadi and Shaebani 2004). Thus, based on these results, a roundabout of around 20 meters of radius seems to perform better than bigger or smaller ones.

The results analysed correspond to a scenario on which: **(i)** all the exits of the roundabout have an equal probability of being chosen by a vehicle to exit it; **(ii)** the human factor does not have influence on the performance of the intersection. However, in a realistic scenario this is not always the case, since on several cases, roundabout accesses may have different inflow and outflow rates. The human factor also has influence on the performance of the roundabout, for instance: when a driver signalizes he is going to exit the roundabout and a second driver trying to enter the roundabout through the same access decides to wait for the first driver to leave the roundabout, instead of entering while the exiting vehicle has not yet exited it; or when the first does not signalize its intention and thus the second must wait. These situations were modelled as percentages processes similar to the one represented on Figure 5. For both cases, a percentage of 50% was considered, albeit it can be adjusted. Thus, simulation experiments were conducted to analyse the impact of these factors on the performance of the intersection. Firstly, different probabilities were assigned to the roundabout destinies (40%, 30%, 20% and 10%). The results can be seen on Table 3.

Table 3: Comparing the modelled unbalanced roundabouts

Traffic intensities	Very high				High				Medium				Low			
Radius (meters)	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
Flow rates (vehicles/hour)	1 511	1 940	1 745	1 622	1 527	1 771	1 582	1 414	1 108	1 108	1 108	1 109	289	289	290	289
Crossing time (minutes)	10,5	7,8	8,6	9,2	7,7	2,4	5,0	5,9	1,1	1,1	1,2	1,3	1,1	1,1	1,1	1,1
Queue size (number of vehicles)	66,2	61,53	61,57	61,03	48,44	10,76	29,08	31,91	0,31	0,11	0,26	0,58	0,06	0,01	0,01	0,02
Total fuel consumed per vehicle (g)	18,6	14,8	15,2	15,5	14,0	5,0	9,1	9,9	2,7	2,7	2,8	3,0	2,6	2,6	2,7	2,8
Total CO emissions per vehicle (g)	3,01	2,42	2,50	2,56	2,32	0,96	1,59	1,74	0,60	0,60	0,64	0,67	0,59	0,60	0,62	0,64
Total HC emissions per vehicle (g)	0,28	0,22	0,23	0,24	0,21	0,07	0,13	0,15	0,03	0,03	0,04	0,04	0,03	0,03	0,03	0,03
Total NOx emissions per vehicle (g)	0,17	0,14	0,15	0,15	0,14	0,07	0,10	0,11	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
Number of stops	34,0	28,5	26,2	24,4	25,4	6,5	14,4	13,5	0,6	0,3	0,5	0,8	0,2	0,2	0,1	0,1

As can be seen, one of the main conclusion drawn from analysing Table 2, can also be observed here, i.e. the size of the roundabout where the best performance was achieved (20 meters of radius). However, it can also be seen that the performance of the roundabout decreased for all cases. In a second phase, the probabilities assigned to the destinies were reset to their default, but a probability of 50% was considered for the human impact factor. The results can be analysed on Table 4.

Table 4: Comparing the modelled roundabouts, considering human factor

Traffic intensities	Very high				High				Medium				Low			
Radius (meters)	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
Flow rates (vehicles/hour)	1 317	1 707	1 487	1 344	1 316	1 706	1 486	1 343	1 108	1 108	1 108	1 108	289	289	289	289
Crossing time (minutes)	12,2	9,1	10,5	11,5	10,7	4,5	8,4	9,7	1,2	1,1	1,2	1,3	1,1	1,1	1,1	1,2
Queue size (number of vehicles)	67,64	63,59	64,21	63,95	59,83	27,66	51,11	53,83	0,63	0,14	0,36	0,95	0,07	0,02	0,02	0,01
Total fuel consumed per vehicle (g)	20,5	16,7	17,9	19,0	18,1	8,8	14,7	16,2	2,8	2,7	2,9	3,1	2,6	2,6	2,7	2,8
Total CO emissions per vehicle (g)	3,31	2,71	2,93	3,11	2,96	1,53	2,44	2,68	0,62	0,61	0,64	0,69	0,59	0,60	0,62	0,64
Total HC emissions per vehicle (g)	0,32	0,25	0,27	0,30	0,28	0,13	0,22	0,25	0,04	0,03	0,04	0,04	0,03	0,03	0,03	0,04
Total NOx emissions per vehicle (g)	0,19	0,16	0,17	0,18	0,17	0,10	0,14	0,16	0,05	0,05	0,05	0,06	0,05	0,05	0,05	0,05
Number of stops	34,7	33,4	33,0	32,8	31,0	16,1	27,0	27,9	0,9	0,4	0,6	1,1	0,3	0,2	0,2	0,2

Once more, the main conclusion regarding the radius of the roundabout, on which the best performance was achieved is maintained (i.e. 20 meters). Nonetheless, by comparing Table 3 and Table 4, it can also be seen that the human factor has a greater influence on the performance of the roundabout than the different probabilities assigned to the roundabout exit lanes. Table 5 shows the results obtained for roundabouts with the two previous scenarios modelled.

Table 5: Comparing the modelled realistic roundabouts

Traffic intensities	Very high				High				Medium				Low			
Radius (meters)	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
Flow rates (vehicles/hour)	1 329	1 686	1 473	1 334	1 330	1 650	1 459	1 331	1 107	1 108	1 108	1 107	289	289	289	289
Crossing time (minutes)	12,1	9,2	10,5	11,5	10,5	4,5	7,0	8,5	1,2	1,1	1,2	1,5	1,1	1,1	1,1	1,1
Queue size (number of vehicles)	67,52	63,63	64,19	63,93	59,43	26,57	40,48	46,44	0,71	0,15	0,43	1,58	0,09	0,01	0,01	0,02
Total fuel consumed per vehicle (g)	20,3	16,7	18,0	18,9	17,9	8,6	12,1	14,2	2,8	2,7	2,9	3,3	2,6	2,6	2,7	2,8
Total CO emissions per vehicle (g)	3,29	2,72	2,94	3,1	2,92	1,51	2,06	2,39	0,62	0,61	0,65	0,72	0,59	0,6	0,62	0,64
Total HC emissions per vehicle (g)	0,31	0,25	0,28	0,3	0,27	0,12	0,18	0,22	0,04	0,03	0,04	0,04	0,03	0,03	0,03	0,03
Total NOx emissions per vehicle (g)	0,19	0,16	0,17	0,18	0,17	0,1	0,13	0,14	0,05	0,05	0,05	0,06	0,05	0,05	0,05	0,05
Number of stops	34,4	32,6	32,5	32,6	30,3	14,9	20,3	23,3	0,9	0,4	0,7	1,6	0,3	0,2	0,1	0,2

Considering both the human factor and the balancing of the roundabout affected more its performance than considering just one of the factors. These roundabouts will be referred as optimistic (Table 2) and realistic (Table 5). Comparing the two in low and medium intensities, it can be seen that there are no significative differences in the performance, for all KPI.

Focusing on the high and very high intensities, the average flow of vehicles can be decreased from 8 to 15% respectively, representing differences of 150 to 300 vehicles/hour. Regarding the crossing time and queue size, the differences are less significative for the highest traffic intensity. In its turn, for the high intensity the differences are more significative, which implies that the highest intensity is so high that both roundabouts could not properly handle these situations - the same conclusion can be withdrawn from the remaining KPI. In this sense, it can be concluded that roundabouts are not the most accurate solution for very saturated traffic situations, which is in accordance to previous studies (Fouladvand, Sadjadi and Shaebani 2003, Skrodenis, Vingrys and Pashkevich 2011). Thus, to accurately evaluate the performance difference between the optimistic and the realistic roundabout, the focus should be put on the high traffic intensity.

In the high traffic intensity, the crossing time per vehicle decreased more than 3 minutes per vehicle, resulting in a decrease in the average queue size of around 90%. This high difference is explained by the fact that only the vehicles that are stopped are accounted for this KPI. The remaining ones, even though they may be on the queue, they are not stopped, which further increases their fuel consumption and emissions. In fact, the average number of stops per vehicle increased up to 88%, culminating in an increase in the fuel consumption in up to 63% - vehicles spend three times more fuel. The respective emissions also increased in the same proportions.

6. CONCLUSIONS

The resolution of traffic congestion problems usually implies the construction of infrastructures such as roundabouts. However, these infrastructures have several decision variables. Thus, this paper proposed a general-purpose discrete-event traffic micro-simulation model that can compare different roundabouts, assessing their performance. The chosen simulation tool – Simio – offers the user the ability to use different simulation paradigms, such as: objective, agent, events, processes and others. Therefore, with some effort it was possible to develop and validate a simulation model in which entities were modelled as intelligent agents, in the sense that they can evaluate their surroundings and make decisions, similarly to what happens in the field.

The conducted simulation experiments concluded that the best size of roundabouts is 40 meters of diameter. The second set of experiments focused on evaluating the human factor in the driving behaviour and the unbalancing of the roundabout in its performance. Thus, a realistic roundabout – considering its unbalancing and

the driving behaviour – and an optimistic roundabout were compared. The main conclusions from this analysis were that the human factor had more negative impact in the performance than the balancing did. In addition, it was concluded that on low, medium and on the highest traffic intensities these roundabouts achieved the same performance, which is in accordance to previous studies (Fouladvand, Sadjadi and Shaebani 2003, Skrodenis, Vingrys and Pashkevich 2011). For the remaining defined traffic intensity – where most significative differences were registered - it was found that the flow of vehicles decreased up to 8% when the optimistic roundabout was compared to the realistic one. It was also found that the scenario corresponding to the unbalanced roundabout and considering the human driving style resulted in a decrease in the waiting time per vehicle in 3 minutes, the queue size in up to 90% and the number of stops per vehicle in up to 88%. Furthermore, it also resulted in an increase in the fuel consumption in up to 63% - vehicles spent three times more fuel - and in the respective emissions.

For future development: (1) it would be interesting to adapt the developed model to handle roundabouts with multi lanes on the approaches, as well as inside the roundabout; (2) since agents are being modelled, it would be interesting to model different types of drivers – accelerate more, or less, requires respectively more, or less, space to enter the roundabout, among others.

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