ROUNDABOUT INTERSECTIONS:
EVALUATION OF GEOMETRIC AND BEHAVIOURAL FEATURES WITH VISSIM

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ABSTRACT

In the literature, there are many methodologies that allow the evaluation of roundabout performances (Capacity, Levels Of Service, etc): analytical models (HCM, HBS etc.), statistical models (TRRL, SETRA) etc. Each technique considers some aspects of the roundabout in comparison to others (geometric elements, vehicular flow and behavioural parameters). Obtained results are often not comparable among themselves because of distinctive peculiarities of each method. Today, the best way to solve this problem is by using a refined simulation software of vehicular circulation. In this paper the authors introduce the results of a wide survey conducted on an ample range of roundabout scenarios by the use of the simulation software VISSIM. Each scenario describes a fixed roundabout phenomenon using the following variables: geometric elements (inscribed circle radius, circulatory roadway, central and splitter islands etc.); characteristics of the traffic flow (dynamic traffic assignment, approach speed, circulatory speed and reduced speed zones, etc.); behavioral features (priority rules, minimum gap, minimum headway, etc.).

The results are presented from the evaluation of stop-line delays.

INTRODUCTION

Many analytical techniques allow the study of the performances (Capacity, Levels of Service, etc) of roundabout intersections: probabilistic methods (HCM *(1)*, HBS *(2)*, etc.), statistic methods (TRRL *(3)*, SETRA *(4)*, etc.).

Each method, when formulated, has to consider some aspects of roundabout circulation in comparison to others (geometric elements, vehicular flow and consumer behaviour).

An approach that allows a global vision of the problem today is through the use of refined simulation analysis software of vehicular circulation.

PERFORMANCES OF ROUNDABOUT INTERSECTIONS

Fundamental Capacity Methods

The capacity of each entry is the maximum rate at which vehicles can sensibly be expected to enter the roundabout during a given time under prevailing traffic and geometric features *(5)*.

Many methods applicable to two-way stop-controlled and two-way yield controlled intersection capacity are used as the foundation for the evaluation of roundabout performances. Roundabout analysis models are generally divided into two categories:

- statistical (empirical) models based on the regression of field data;
- analytical (semi-probabilistic) models based instead on the gap-acceptance theory.

Empirical models correlate geometric features and performance measures, such as capacity, average delay and queue length, through the regression of field data. In this way they generate a relationship (generally linear or exponential) between the entering flow of an approach and the circulating flow in front of it *(6)*. These models are better than analytical ones but require a great number of congested (oversaturated conditions) roundabouts for calibration and may have poor transferability to other countries *(7)(8)*.

Gap-acceptance models can be developed instead from uncongested sites: the driver on the approach (entering flow) needs to select an acceptable gap in the circulating stream, to carry out the entering manoeuvre. The gap is the headway between two consecutive vehicles on the circulating flow: so the "critical gap" (t_c) is the minimum headway accepted by a driver in the entering stream. If the gap accepted is larger than minimum, then more than one driver can enter the roundabout: the time required for an additional vehicle to utilize the same gap in traffic, is defined as "follow-up time" (t_f). So these analytical models calculate the roundabout capacity as a function of the critical gap, the follow-up time and the circulating flow. However, for capacity evaluation there are some assumptions:

1. constant values for "t_c" and "t_f";
2. exponential distribution for the gaps into the circulating flow;
3. constant traffic volumes for each traffic flow.

These specific assumptions make the use of these models difficult in practice. Furthermore, there are other limitations, such as:

1. the estimation of the critical gap is not easy;
2. the geometric factors are not directly taken into account;
3. the inconsistent gaps are not accounted for in theory (forced right of way when traffic is congested, circulating drivers give up right of way, different gap accepted by different vehicles, the rejection of large gap before accepting a smaller one, etc.).

A summary of the majority of international methods for the evaluation of roundabout capacity is represented in *(6)*.

Micro-Simulation Software Packages

The ever increasing use of roundabouts to solve traffic problems has produced a great number of models which are able to predict operational performances. Each of these methods allows many important roundabout features to be estimated such as capacity, average delay and queue length, by the use of empirical or analytical formulations. In particular the theory of gap-acceptance leads to complex assumptions regarding driver behaviour and often it is not easy to obtain good results for atypical roundabout geometries *(8)*. In order to solve this problem there are various software packages that provide roundabout analysis, using several theoretical methods and requiring a variety of input parameters.

However, not many software packages allow the user to model roundabouts exactly. These packages can be divided into two categories: deterministic (empirical or analytical) and stochastic simulation models *(9)*. The first ones, such as SIDRA, Rodel, Arcady, Kreisel, etc., analyze roundabout performance with a series of equations, correlating these features (e.g. delay, queues, capacity) with a set of variables. The second ones instead (e.g. Vissim, Corsim, Integration), use an interval-based simulation to describe traffic operations.

A summary of the principal international software packages for roundabout feature simulation is shown in Table 1.

TABLE 1 Summary of The Principal Softwares for Roundabouts Simulation

COUNTRY	NAME	MODEL	NEWLY REFERENCE
U.K.	RODEL	Deterministic Empirical	*(10)*
U.K.	ARCADY	Deterministic Empirical	*(11)*
U.K.	PARAMICS	Stochastic Simulation	*(12)*
Australia	SIDRA	Deterministic Analytical	*(3)*
Germany	KREISEL	Deterministic All methods	*(11)*
Germany	VISSIM	Stochastic Simulation	*(13) ; (14)*
U.S.A.	HCS/SYNCHRO	Deterministic Analytical	*(14)*
U.S.A.	CORSIM	Stochastic Simulation	*(15)*
U.S.A.	INTEGRATION	Stochastic Simulation	*(16)*
U.S.A.	SIMTRAFFIC	Stochastic Simulation	*(16)*
France	GIRABASE	Deterministic Empirical	*(17)*
Spain	GETRAM	Stochastic Simulation	*(18)*

A Microscopic Simulation Model: Vissim

The simulation of roundabout traffic operations often presents many complexities, because it is not easy to define all the geometric and user-behavioural features. Vissim gives a flexible platform that allows the user to more realistically model a roundabout. It is based on a link-connector instead of a link-node structure which is easily able to build a complete network or, specifically, a single intersection. In addition, Vissim is able to import CAD layout (dxf or jpg) and to set it as a background on which links can be drawn. An appropriate scale is assigned, so that all the measurements are in the same units. In this way it allows, for example, all the geometric elements of a roundabout (splitter islands, lane width, number of lanes, entry width, etc.) to be precisely drawn. Anyway, there are three principal features which are very important to set in order for a correct simulation: 1) approach speed, reduced speed zones and circulatory speed; 2) priority rules; and finally, 3) traffic assignment.
Furthermore the driver behavior is also important: Vissim uses a psycho-physical car following model and a rule-based algorithm for lateral movements realized by Wiedemann ('74).

Approach Speed, Circulatory Speed And Reduced Speed Zones

An accurate definition of the vehicle speeds is very important to achieve a good simulation of a roundabout.

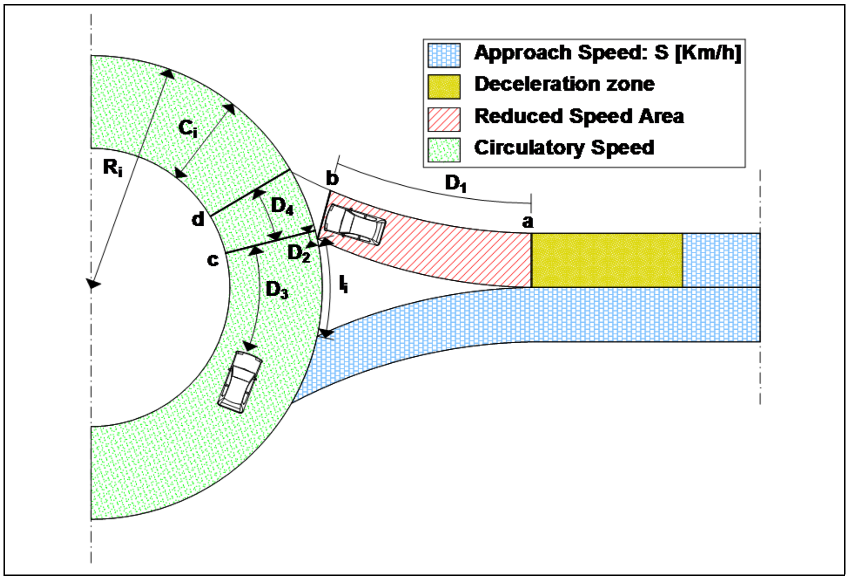


FIGURE 1 Description of the principal parameters used in Vissim for circulation rules.

Vissim allows the definition of the desired speed of every type of vehicle when the said vehicle enters the network. The approach speed of every leg of the roundabout is taken in a range defined by an empirical speed curve which is created by the user: this curve usually presents an S-form (normal distribution). The vehicles maintain the desired speed until traffic conditions or geometric features require them to change it *(19)*. Vissim uses reduced speed zones in order to change the desired speed: these have been used to set the influence of roundabout entry geometry on the approach speed. The reduced speed zones assign a new speed distribution to the vehicles which begin to decelerate before the start of the same areas (see "deceleration zone" in Figure 1). After the end of these zones the vehicles begin to accelerate in order to reach the previous desired speed if the user does not set a new one. Specifically, for roundabouts, after the reduced speed area of the entry, a Circulatory Speed distribution is set which is derived from vehicle radial dynamics equilibrium:

$$V = \sqrt{127 \cdot R \cdot (q + f_t)} \qquad (1)$$

With these assumptions: $q=0$; $f_t=0.23$; $R=R_i-(C_i/2)$.

This equation allows the average speed (V_m) to be obtained of the circulating vehicles into the roundabout and the range of the circulatory speed distribution to be set. In fact, considering this as a normal distribution and considering standard deviation σ=5Km/h (this is derived from field data), it is therefore possible to define the extreme values of the range as $V_m \pm (1,96 \cdot \sigma)$ in order to consider the 95th percentile of the circulatory speed.

Priority Rules

The most important aspect to modelling a roundabout in Vissim is to correctly define the priority rules for entering and exiting movements (for a one-lane-roundabout there are only priority rules for entering vehicles). These rules are based on two fundamental parameters: minimum gap time and minimum headway, see Figure 1.

A vehicle, which is standing at the stop-line, enters the circulatory roadway only when the time gap and headway $\mathbf{D_3}$ measured from the conflict markers are greater than the relative minimum values. A priority rule is usually composed of a stop line (**b**) and one or more conflict markers, **c** and **d** in this case.

In particular, **c**, placed distance $\mathbf{D_2}$ over the right corner of the splitter island, is used to set the minimum gap time and the minimum headway for normal traffic conditions; while **d** placed distance $\mathbf{D_4}$ over the conflict marker 1 (**c**), is used to define only the minimum headway for congested conditions. It is possible to set different values of minimum gap (as it will be shown in experimental results, in Vissim, this parameter is very important) or headway for any type of vehicle, but in this case only traffic flows measured in "equivalent vehicles per hour" are considered. So both marker conditions must be satisfied for a vehicle to enter the roundabout.

Traffic Assignment

As traffic input data, Vissim uses only an O/D matrix, which contains the number of movements for each origin/destination during a specific time range.

EXPERIMENTAL PLANNING

The study proposed was conducted through the use of the VISSIM micro-simulator (release 4.0) *(19)*.

The imposed inputs are pointed out in synthesis below (see Figure 2 (b) concerning values):

- distribution and assignment of traffic flow in time and space;
- implementation of circulation rules: approach speed, reduced speed zones, circulatory speed zones and priority rules;
- setting up of scenarios to be analyzed (choice of geometric and traffic variables).

Recorded outputs are represented by the average stop-line delay.

Distribution And Assignment Of Traffic Flow

In the experimental planning introduced in this paper, four separate traffic flows TF_i (with i=1,…,4 - only motorcars) are considered, see Table 2. The traffic flows were distributed in the time and in the space as shown in Figure 2 (a):

- the flow-time curve of traffic demand was obtained in accordance with a theoretical curve *(20) (21)*. TF_i is the total entering flow of an approach during an hour. This flow was distributed as is shown in Figure 2 (a), where:

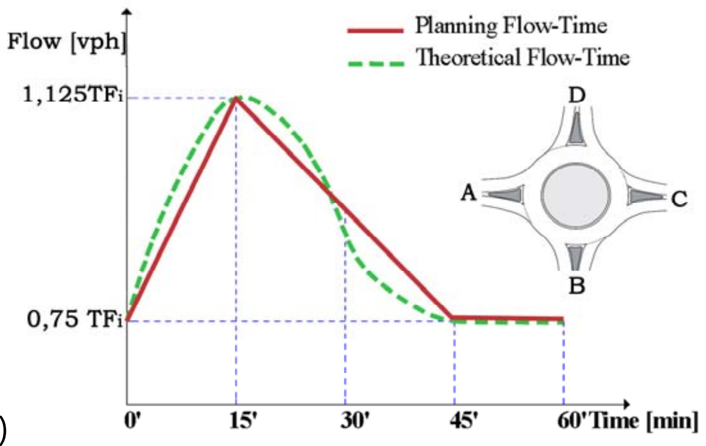
$$TF_{i_{\min}} = 0.75 \cdot TF_i \qquad TF_{i_{\max}} = 1.5 \cdot TF_{i_{\min}} = 1.125 \cdot TF_i \tag{2}$$

- the O/D matrixes used have a balanced traffic flow distribution (unbalanced flow distributions will be considered in future researches).

In this way, for each traffic flow (TF_i) was created four different O/D matrixes: one for every quarter of an hour.

As regard instead the circulation rules, the values used are shown in Figure 2(b).

As far as reduced speed areas is concerned (into various scenarios), it was chosen three different lengths "D_1", see Figure 2(b) . Each of these ones was marked by a speed distribution correlated to the approach speed and to the circulatory speed (which is variable with R_i).



(a)

	A	B	C	D
A	-	1/8	6/8	1/8
B	1/8	-	1/8	6/8
C	6/8	1/8	-	1/8
D	1/8	6/8	1/8	-

	Turn on the right
	Turn on the left
	Crossing

D_1	$D_1^{S1} = 56.4$m; $D_1^{S2} = 69.3$m; $D_1^{S3} = 82.1$m		
D_2	0,5m		
D_3	If circulatory speed is ⇒	15÷50km/h ⇓	≤ 15km/h ⇓
		Conflict Marker **c**	Conflict Marker **d**
	Time Gap	3,0 s ÷ 3,5 s ÷ 4,0 s	0 s
	Headway	5m	5m
D_4	4m		

(b)

FIGURE 2 (a) Theoretical curve of traffic and planning demand used in the micro-simulation and O/D matrix used for traffic flow distribution; (b) Values used for circulation rules.

Setting Up Of Scenarios

Three separate sets of scenarios for single-lane roundabouts were composed and analyzed, (see Figure 3 and Table 2), in total, 432 scenarios:

- R-Scenarios. They have the following variables: Traffic Flow (TF_i), approach Speed (S_i), inscribed circle Radius (R_i), Time Gap (TG_i);
- I-Scenarios. They have the following variables: Traffic Flow (TF_i), approach Speed (S_i), splitter Island width (I_i), Time Gap (TG_i);
- C-Scenarios. They have the following variables: Traffic Flow (TF_i), approach Speed (S_i), Circulating roadway width (C_i), Tme Gap (TG_i).

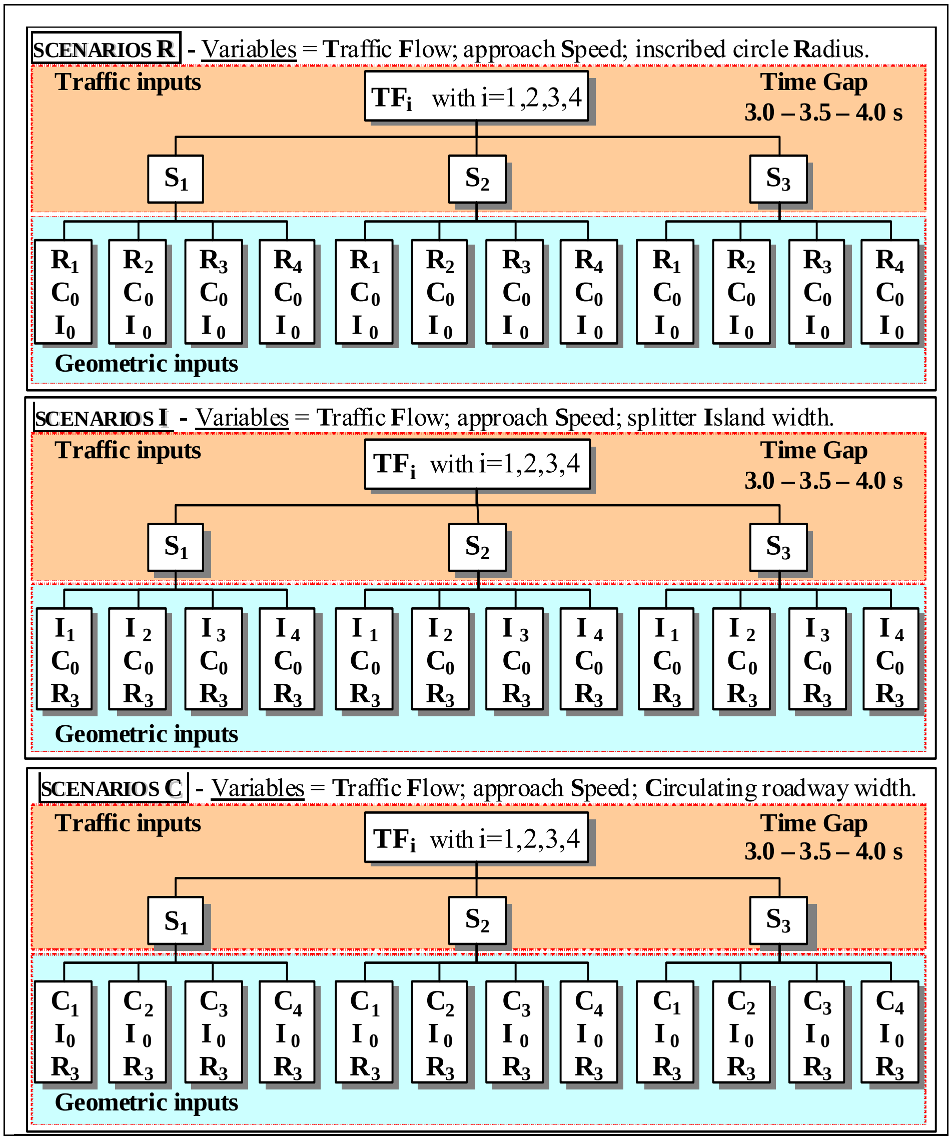


FIGURE 3 Sets of scenarios analyzed.

TABLE 2 Summary of The Imposed Values to Inputs Data

PARAMETERS	INPUT DATA
Traffic Flow	TF_1=350vph; TF_2=500vph; TF_3=600vph; TF_4=650vph.
Approach Speed	S_1=30÷40km/h; S_2=40÷50km/h; S_3=50÷60km/h.
Inscribed Circle Radius	R_1=15m; R_2=20m; R_3=25m; R_4=30m.
Splitter Island Width	I_0=6m; I_1=8m; I_2=10m; I_3=12m; I_4=14m.
Circulating Roadway Width	C_0=6m; C_1=7m; C_2=8m; C_3=9m; C_4=10m (only single-lane).
Time Gap	TG_1=3.0 s; TG_2=3.5 s; TG_3=4.0 s;

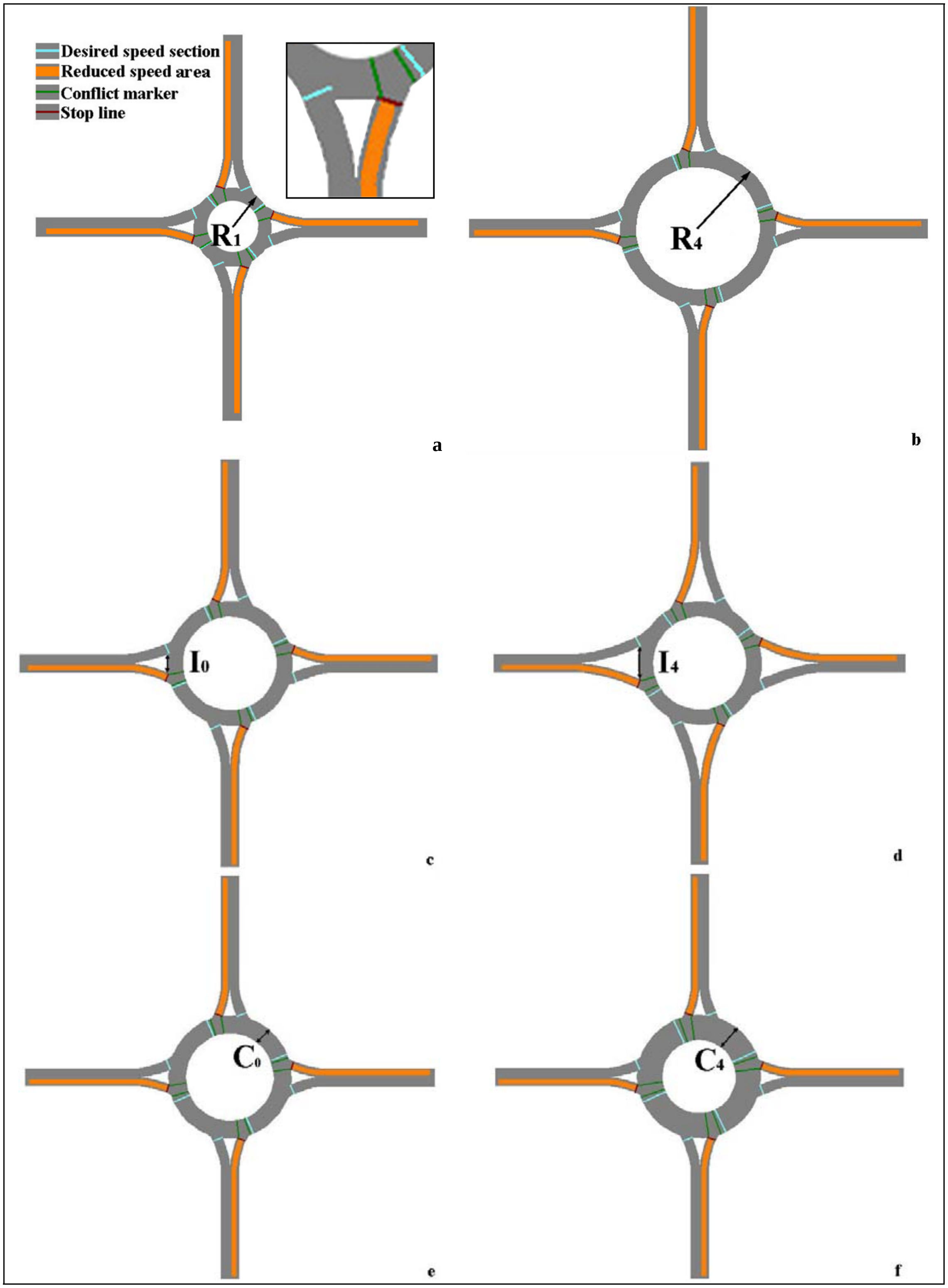


FIGURE 4 Some Vissim screenshots of the modeled roundabouts used for simulations: a) and b) for R-scenarios; c) and d) for I-scenarios; e) and f) for C–scenarios.

Figure 4 shows some Vissim screenshots of the modeled roundabouts, pointing out (with different colours) particular features such as: desired speed sections; reduced speed areas; conflict markers and stop lines.

EXPERIMENTAL RESULTS AND DATA ANALYSIS

Vissim, as with all micro-simulation software programs, simulates traffic in a *one-shot* simulation; therefore, to get a statistically valid estimate of stop-line delays, n° 3 simulations were made for each sets of scenarios (multiple-run simulations with running time of one hour for each simulation).

In Figures 5, 6, 7, 8, 9 and 10 the results will be introduced obtained by the micro-simulations for each sets of scenarios analyzed in terms of average stop-line delays. A travel time route was coded for each approach in order to obtain delay (data collection points placed on the stop line of the entries). Having considered only balanced traffic flow distributions, the final value of delay for each scenario is the average of all the values calculated for the multiple-run simulations and for all four legs of roundabout.

Anyway for thoroughness, it is opportune to show that the average values of stop-line delay obtained (see, graphics in Figures 5, 6, 7, 8, 9 and 10) have shown standard deviation values included into the variability ranges pointed out in Table 3.

In particular, the variability of these ranges of standard deviation is principally due to the traffic flow distribution chosen for the simulation, see Figure 2(a).

TABLE 3 Summary of The Variability Ranges of Standard Deviation of Stop-Line Delay for The Different Scenarios (as Percentage of The Average Value of Stop Line Delay)

		R-Scenarios			*I-Scenarios*			*C-Scenarios*		
		S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
TG_1	*Dev. St min (%)*	35,7%	33,0%	35,7%	36,8%	38,3%	33,2%	37,1%	35,3%	33,2%
	Dev. St max (%)	62,4%	66,2%	62,4%	64,0%	61,1%	61,2%	62,3%	62,9%	61,2%
TG_2	*Dev. St min (%)*	20,9%	24,7%	19,2%	20,9%	27,3%	25,6%	20,0%	19,7%	21,8%
	Dev. St max (%)	61,6%	58,4%	71,6%	61,0%	61,1%	61,8%	59,5%	60,3%	56,2%
TG_3	*Dev. St min (%)*	35,7%	33,0%	32,4%	36,8%	38,2%	33,2%	35,3%	37,1%	33,2%
	Dev. St max (%)	62,4%	62,0%	64,0%	64,0%	61,1%	61,2%	62,9%	62,3%	61,2%

R - Scenarios

The R-Scenarios are characterized by following geometric variable: inscribed circle Radius (R_i). In Figures 5 and 6 the average stop-line delays are represented in terms of Traffic Flow (TF_i), approach Speed (S_i) and Time Gap (TG_i).

For all the considered R-scenarios, the approach speed seems not to show particular influences on stop-line delay, see Figure 5 and 6.

By the analysis of Figures 5 and 6 it is possible to affirm that:

- for all Traffic Flows (TF_i with i=1,2,3,4) and for each R_i (with i=1,2,3,4), if Time Gap increases stop-line delay increases are recorded.

In particular, see Figure 5:

- for low Traffic Flow, TF_1=350vph, for each TG_i (with i=1,2,3) and R_i (with i=1,2,3,4) varies, stop-line delay is almost constant and lower than 10 sec (Level of Service A, *(1)*). It is plain that for this class of scenarios (to low traffic flow) the variation in R (and therefore of the circulating speed) determines a poor variability of the stop-line delays;

- for Traffic Flow, TF_2 =500vph, and Time Gap equal to TG_1 and TG_2, if R_i (with i=1,2,3,4) varies, stop-line delay is almost constant and lower than 20 sec (Levels of Service A-B-C) *(1)*. For Time Gap equal to TG_3, if R_i (with i=1,2,3,4) increases, stop-line delay increases up to ≅ 60 sec (Levels of Service D-E-F, *(1)*).

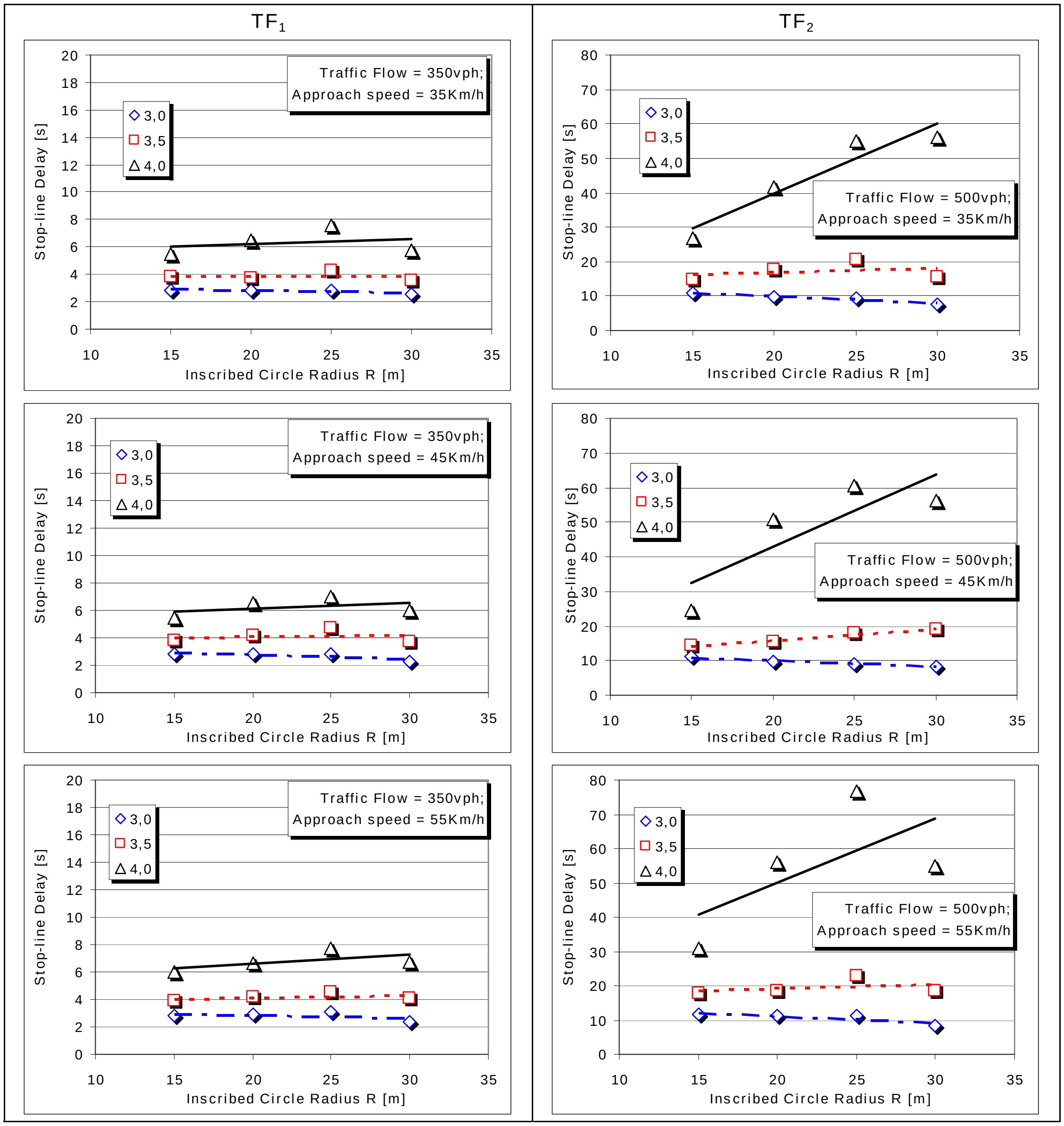


FIGURE 5 Average Stop-line delays for R-Scenarios (TF_1 and TF_2).

By the analysis of Figure 6 it is possible to affirm that:

- for Traffic Flows TF_i with i=3,4, Time Gap equal to TG_2 and TG_3, if R_i (with i=1,2,3,4) increases, stop-line delay increases are recorded (Level of Services F, *(1)*); opposite for minimum Time Gap (TG_1), if R_i (with i=1,2,3,4) increases, stop-line delay decreases.

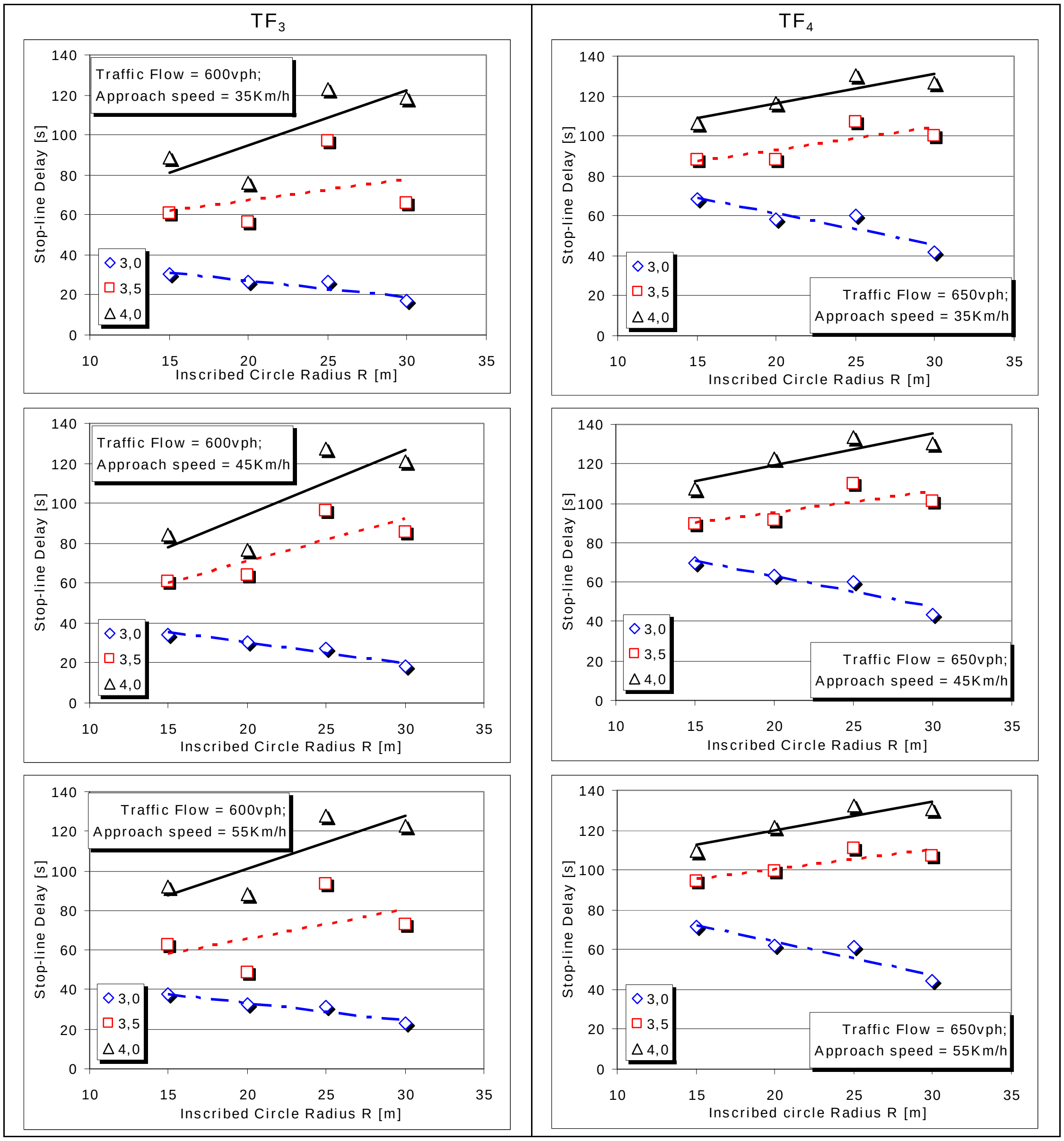


FIGURE 6 Average Stop-line delays for R-Scenarios (TF_3 and TF_4).

In general, in according to the equation (1) when R_i increases, circulatory speed increases too (Max ΔSpeed ≈ 9km/h). Furthermore, even more important, it is that when R_i increases, length of circulatory roadway increases (Average ΔLength ≈ 95m), see Figures 4(a) and 4(b).

What was stated above implies that there is a greater rate of vehicular occupation of the circulatory roadway, if combined both with the increase of traffic by TF2 to TF4 and the car-following model (not modified by the authors with respect of default parameter). As a direct consequence of this it happens that the average spacing among the vehicles is the smallest. For example, for traffic flow TF4 and for TG_2 and TG_3, if R increases stop-line delay increase; while for TG1, if R increases stop-line delay decreases.

I - Scenarios

The I-Scenarios are characterized by following geometric variable: width of splitter island (I_i). In Figures 7 and 8 the average stop-line delays are represented in terms of Traffic Flow (TF_i), approach Speed (S_i) and Time Gap (TG_i).

For all the considered I-scenarios, the approach speed seems not to show particular influences on stop-line delay, see Figure 7 and 8.

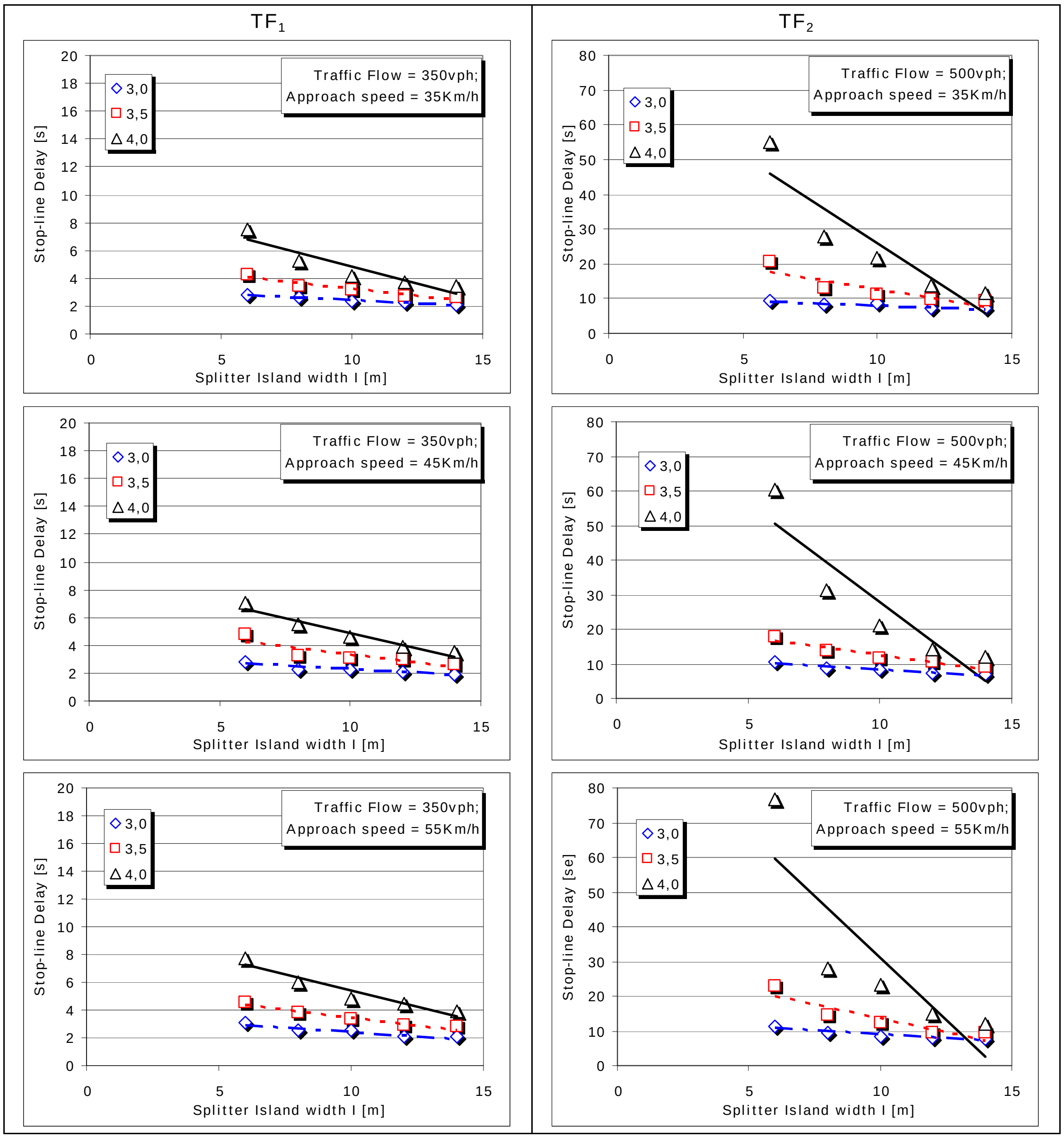


FIGURE 7 Average Stop-line delays for I-Scenarios (TF_1 and TF_2).

By the analysis of these Figures it is possible to affirm that:

- for all Traffic Flows (TF_i with i=1,2,3,4) and for each I_i (with i=1,2,3,4,5), if Time Gap increases stop-line delay increases are recorded;
- for all Traffic Flows (TF_i with i=1,2,3,4) and for each TG_i (with i=1,2,3), if I_i increases then stop-line delay decreases.

In particular, see Figure 7:

- for low Traffic Flow, TF_1=350vph, whenever I_i (with i=1,2,3,4,5) varies, anyway stop-line delay is lower than 8 sec (Level of Service A, *(1)*);
- for Traffic Flow, TF_2=500vph, for each Time Gap, if I_i tends to 6 m then stop-line delay increases pseudo-exponentially (stop-line delay more than 50 sec);
- for Traffic Flow, TF_2 =500vph, Time Gap equal to TG_1 and TG_2, in any case stop-line delay remains lower than 20 sec (Levels of Service C, *(1)*).

By the analysis of Figure 8 it is interesting to notice that:

- for Traffic Flows TFi with i=3,4, for each Time Gap, if Ii increases, stop-line delay instead decreases appreciably.

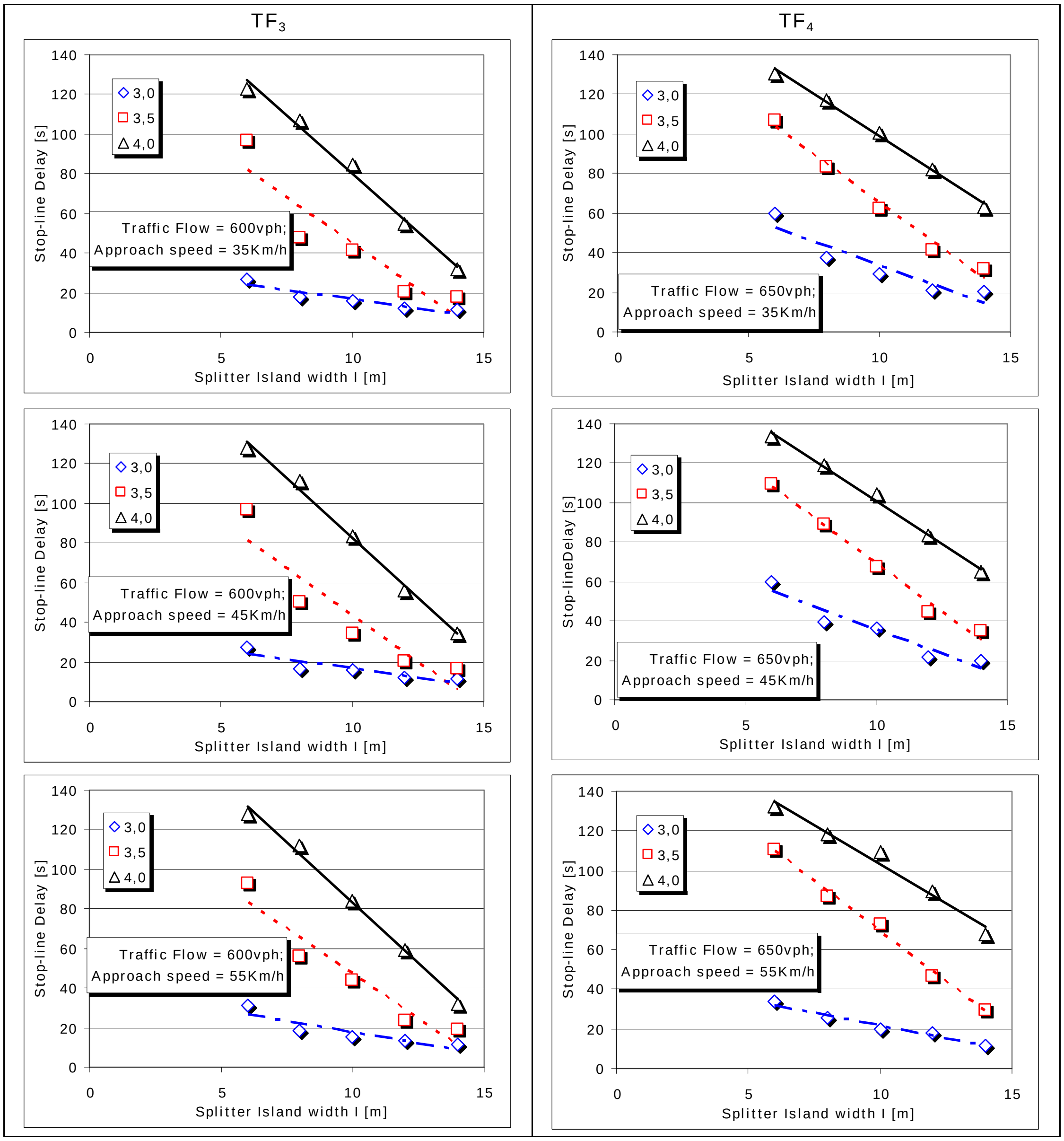


FIGURE 8 Average Stop-line delays for I-Scenarios (TF_3 and TF_4).

In brief, for TF_i (with i=1,2,3) and for TG_i (with i=1,2,3) the stop-line delay values seem to converge to an only value for I_4=15m: the simulation model seems to interpret well some “historic” and consolidated indications in literature *(4)*.

However, it is opportune to underline that in the design practice, if splitter island is excessively great, it can involve risky shortenings of waving section along the circulatory roadway.

Moreover , roundabouts have often also been used successfully at the interface between rural and urban areas where speed limits change *(5)*. In these applications, if splitter island is excessively great, the traffic calming effects of roundabouts are minimized.

C - Scenarios

The C-Scenarios are characterized by following geometric variable: width of circulating roadway (C_i). In Figures 9 and 10 the average stop-line delays are represented in terms of Traffic Flow (TF_i), approach Speed (S_i) and Time Gap (TG_i).

For all the considered S-scenarios, the approach speed seems not to show particular influences on stop-line delay, see Figure 9 and 10.

The results reported are correlated with some important setting parameters used in Vissim: one only lane in circulatory roadway, vehicle in free flow in middle position within the lane, no overtake on same lane.

By the analysis of these Figures it is possible to affirm that:

- for all Traffic Flows (TF_i with i=1,2,3,4) and for each C_i (with i=1,2,3,4,5), if Time Gap increases stop-line delay increases are recorded;
- for all Traffic Flows (TF_i with i=1,2,3,4) and for each TG_i (with i=1,2,3), if C_i increases then stop-line delay decreases.

In particular, see Figure 9:

- for low Traffic Flow, TF_1=350vph, whenever C_i (with i=1,2,3,4,5) varies, anyway stop-line delay is lower than 8 sec (Level of Service A, *(1)*);
- for Traffic Flow, TF_2=500vph, Time Gap equal to TG_1 and TG_2, in any case stop-line delay remains lower than 25 sec (Levels of Service C, *(1)*).

Finally, see Figure 10:

- because of high Traffic Flows, TF_3 and TF_4, C_i (with i=1,2,3,4,5) and TG_i (with i=1,2,3) varies, trendy line of stop-line delay are comparable in terms of quality and quantity.

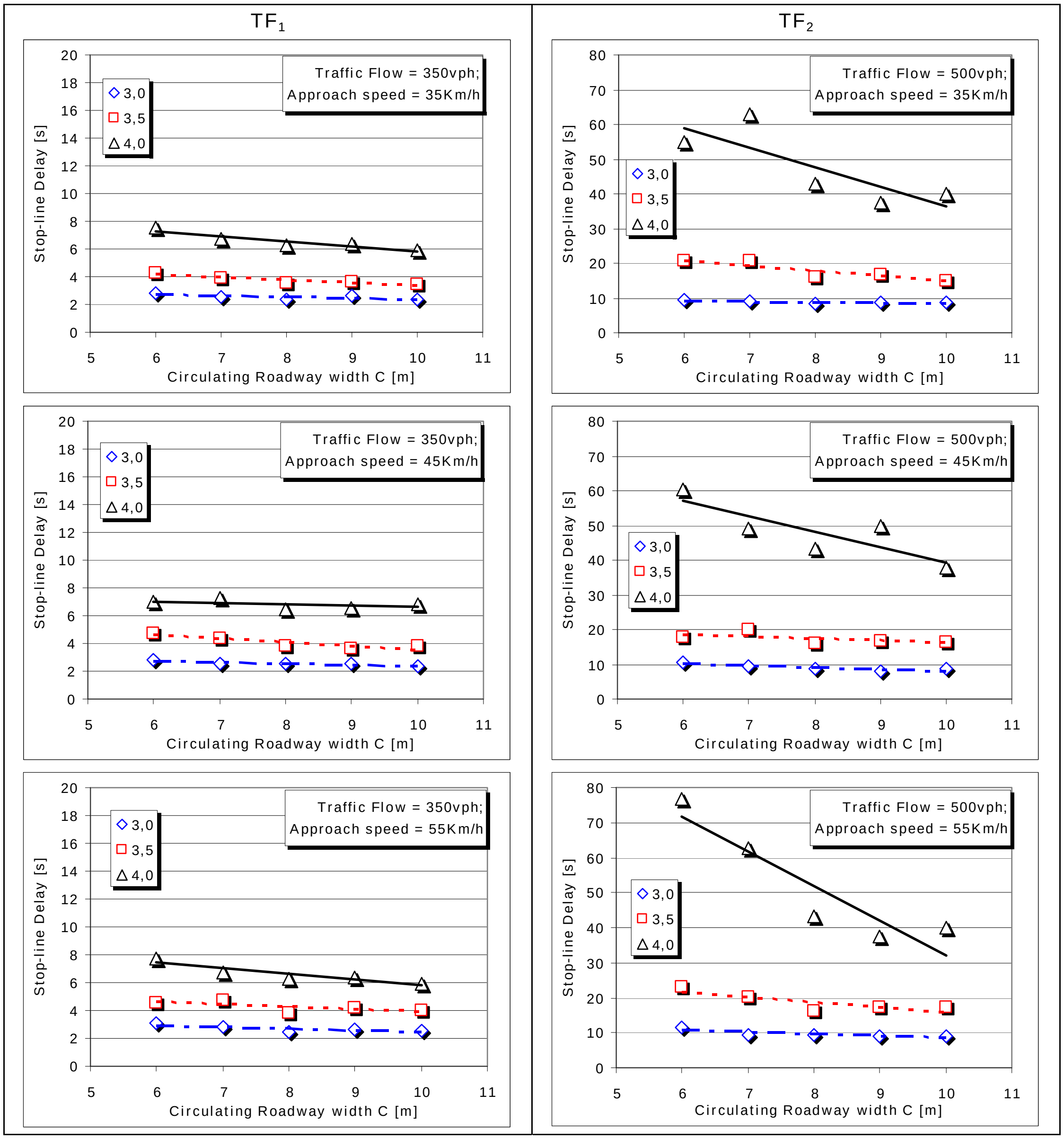


FIGURE 9 Average Stop-line delays for C-Scenarios (TF_1 and TF_2).

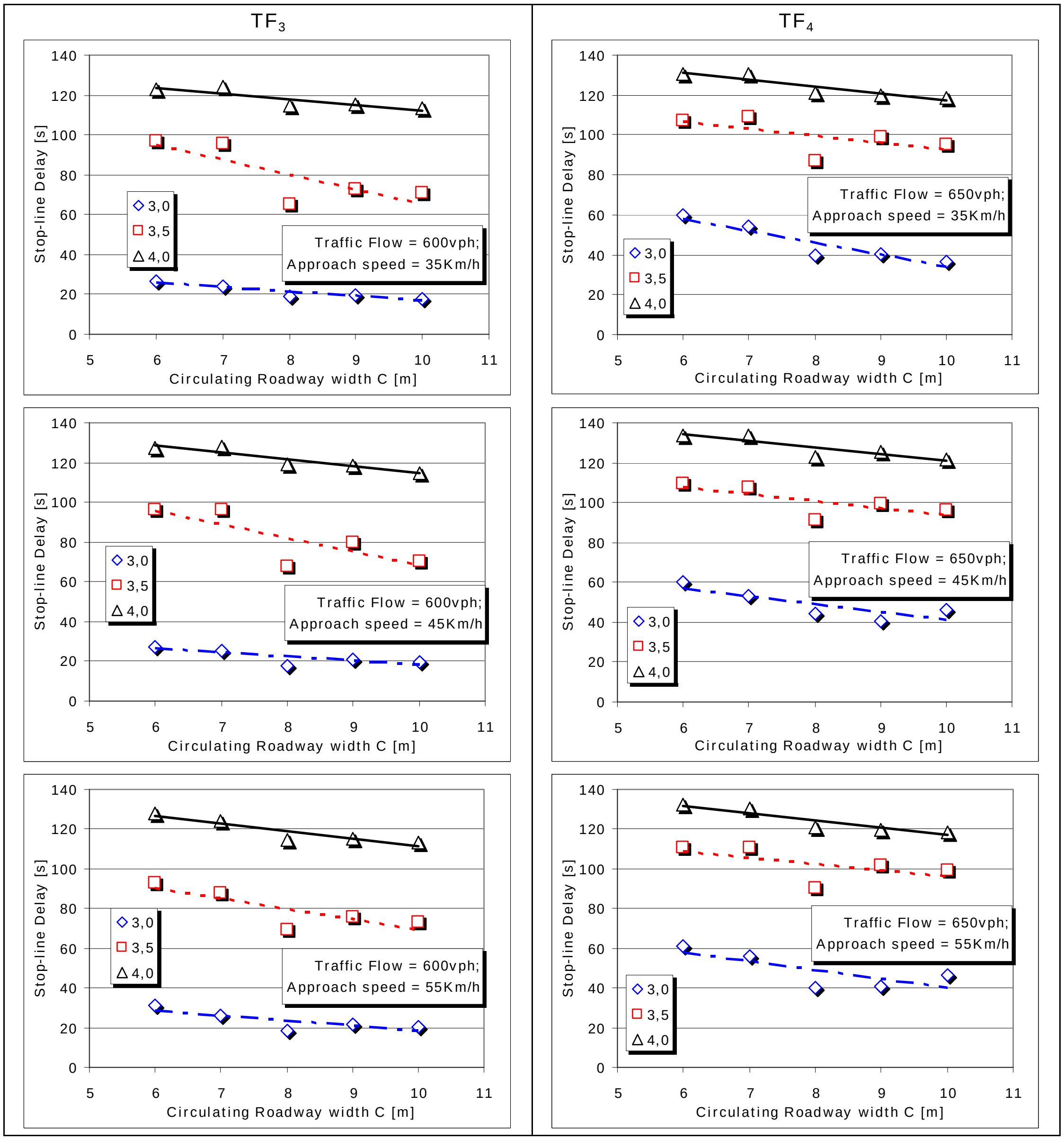


FIGURE 10 Average Stop-line delays for C-Scenarios (TF_3 and TF_4).

CONCLUSIONS

In this paper three different sets of scenarios for single-lane roundabouts were analyzed by a micro-simulator: R-scenarios, I-scenarios C-scenarios. Inscribed circle radius, splitter island width and circulating roadway width respectively represented the variables of each scenarios, while traffic flow, approach speed and time gap was imposed as parametric variables for every scenario. In total, 432 scenarios were analyzed.

The interpretation of results has allowed interesting correlations to be obtained between stop-line delay, geometric variables and parameters of simulation coding. The results have underlined, however, a strong dependence of the stop-line delay from the value of the time gap assumed; this it is even more marked for high traffic flows, of course.

Anyway, the comparison among data field and micro-simulation data is very important, in fact, it is this control that allows a best setting of the micro-simulator inputs. Recently, in this direction the Authors proposed the first interesting results *(7)*.

Finally, this paper could be useful to users of simulation models who are trying to understand the sensitivity of the model to different input parameters.

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