Comparison Between Existing Accident Models and Surrogate Safety Assessment Models (SSAM) on Unconventional Roundabouts, with Focused Applications of the Latter to some Real Study Cases

Antonio Pratelli
Department of Civil and Industrial Engineering
University of Pisa
Pisa, Italy
e-mail: antonio.pratelli@unipi.it

Lorenzo Brocchini
Department of Civil and Industrial Engineering
University of Pisa
Pisa, Italy
e-mail: lorenzo.brocchini@phd.unipi.it

Pietro Leandri
Department of Civil and Industrial Engineering
University of Pisa
Pisa, Italy
e-mail: pietro.leandri@unipi.it

Rosaria Aiello
Department of Civil and Industrial Engineering
University of Pisa
Pisa, Italy
e-mail: aiello.sara91@gmail.com

***Abstract*— This article has been divided into two main parts. The first and most substantial part describes the comparison between the expected number of accidents calculated through analytical models and the Surrogate Safety Assessment Model (SSAM) of the Federal Highway Administration (FHWA), regarding unconventional roundabouts. The novelty of this comparison lies precisely in the fact that the three roundabouts analysed fall into the category of so-called Unconventional Roundabouts, i.e., arrangements with "roundabout circulation", which do not fall within the types listed in the Italian Guidelines. In any case, apart from this latest innovation coupled with the small size of the sample observed, the present work can be considered an exploratory study with a view to further development. Returning to talk about roundabouts, it is possible to state that among the various types of accidents that may occur, those of the rear-end collision type occur more frequently, for which it was decided to use the formulas of the accident models relating to this type of conflict. In particular, the conflict type "Approach" for the Maycock & Hall model and the conflict type "Rear end" for the Arndt & Troutbeck model were taken into consideration. In addition to the application of analytical models, possible points of conflict (of the same category, i.e., "Rear end") were evaluated using dynamic simulation models. In particular, the dynamic simulation software Aimsun™ was used as a means to obtain the necessary inputs for the evaluation of the surrogate safety carried out through SSAM, a software application that reads the trajectory files generated by the simulation programs. The second part of the article instead focuses on the application of SSAM to two real case studies for which, thanks to the results obtained, it was possible to demonstrate the effectiveness of the proposed solutions. At the end of this work, both the conclusions on the comparison made and on the application of SSAM to real cases have been inserted.**

Keywords- Unconventional Roundabouts; Microsimulations with Aimsun; SSAM; Accidents Models; Real Case Studies.

I. INTRODUCTION

This article is an extended version of the conference paper "Comparison between Surrogate Safety Assessment Models (SSAM) and Accident Models on Unconventional Roundabouts" [1], presented at the Twelfth International Conference on Data Analytics in September 2023. In the first part, the comparison between the expected number of accidents calculated through analytical Accident Models and the Surrogate Safety Assessment Model (SSAM) of the Federal Highway Administration (FHWA), regarding unconventional roundabouts will be described. In the second part instead a focus on SSAM application, employed for two real case studies, will be illustrated.

Anyway, the whole research work starts from the idea of the authors to develop the work carried out by Vasconcelos et al. in the article "Validation of the Surrogate Safety Assessment Model for Assessment of Intersection Safety" [2]. In particular, the authors have decided to resume the research work carried out and extend it with their contribution, starting from their conclusion that the Surrogate Safety Assessment Model is a quite promising approach to assessing the safety of new facilities, innovative layouts and traffic regulation schemes. Then, the present work started from the fact that it is difficult to calculate the possible number of accidents in roundabouts with innovative layouts, because, unlike the conventional ones which are "geometrically identifiable", they have highly variable geometric parameters and therefore it is difficult to able to describe their road safety with a single model.

So, this research tried to describe the comparison between the Surrogate Safety Assessment Model (SSAM) of the Federal Highway Administration (FHWA) and the predicted number of accidents calculated through analytical models, regarding Unconventional Roundabouts. The extension of the work of Vasconcelos et al. [2] and therefore the novelties lie precisely in the fact that the three roundabouts analysed fall precisely into the category of so-called Unconventional Roundabouts, i.e., arrangements with "roundabout circulation", which do not fall within the types listed in the Italian Guidelines (Ministerial Decree 19-04-2006: "Functional and geometric rules for the construction of road intersections" [3]).

As said above, despite the innovations just highlighted, the significance of the study is mitigated by the limited size of the sample in question. Consequently, this work should be considered primarily as an exploratory effort, laying the foundation for future investigations aimed at refining and implementing a new possible study model. Thus, this preliminary study could serve as a springboard for deeper exploration and more comprehensive research for future advances in this area. In any case, although the present study represents just a preliminary exploration, its implications are already important, because they pave the way for future developments that have the potential to redefine the approach to computational modelling of Unconventional Roundabout safety.

Going back to talking about them, these roundabouts have shapes and dimensions that are out of the ordinary concept of roundabout intersection. As regards the accident models, it was decided to consider the formulas of the conflict type "Approach" for the Maycock & Hall [4] model and those of the conflict type "Rear end" for the Arndt & Troutbeck [5] model.

This choice is based on the fact that among the various types of accidents that can occur in roundabout intersections, rear-end collisions occur more frequently (literature the values vary from 20% to 25%). As far as the surrogate safety evaluation is concerned, it was carried out using SSAM (a software application that reads the trajectory files generated by the simulation programs) [6]. It was decided to use Aimsun™ as a dynamic microsimulation software, with which it was possible to obtain the ".trj files", i.e., the trajectory files, essential for calculating the possible points of conflict, which, by definition, are the points where two vehicles can potentially collide with each other at road intersections. Also, in this case, the points of conflict of the "Rear end" category have been taken into consideration.

Finally, to improve the visualization style of the points of conflict extrapolated from SSAM, it was decided to use the software Quantum Geographic Information System (QGIS); in this application, the files extrapolated from SSAM were inserted and geolocated.

The extended part of this work instead concerned a focus on SSAM application, employed for two real case studies. This idea was developed starting from one of the conclusions regarding the comparison between SSAM and Accident Models, i.e., that also for Unconventional Roundabouts there is a correspondence between the accident models and the calculation of the conflicts carried out with SSAM.

Thanks to this consideration, it was therefore possible to apply the SSAM model to two real cases. In detail, the first real case is nothing more than an Unconventional Roundabout (and, in particular, a Double Raindrop Roundabout) and the second, even more distinctive, is a Motorway Tollbooth.

The following sections will follow: a first more theoretical section which will deal with the Italian Unconventional Roundabouts with some examples that are taken into consideration; two sections concerning the existing roundabouts accident models and the SSAM approach from FHWA; a section, which will explain the comparison of the two approaches; the last section, followed then by the conclusions, will be focused on the application of SSAM approaches on the two real case studies.

II. ITALIAN UNCONVENTIONAL ROUNDABOUTS

The subsections that follow will primarily deal with the theory of the so-called Unconventional Roundabouts, referring to the Italian Guidelines; and then move on to the three practical instances which were used to carry out the comparison between existing Accident Models and Surrogate Safety Assessment Models (SSAM).

A. Unconventional Roundabouts and Italian Guidelines

First of all, it is appropriate to specify what is meant by Unconventional Roundabouts [7] and why the authors decided to develop their research on them. In the Italian guidelines (Ministerial Decree 19-04-2006 [3]), there can be three basic types of roundabouts based on the diameter of the outer circumference: Conventional Roundabouts with an outer diameter between 40 and 50 m; Compact Roundabouts with outside diameters between 25 and 40 m; Mini Roundabouts with external diameter between 14 and 25 m. For arrangements with "roundabout circulation", which do not fall within the above typologies, we, therefore, speak of Unconventional Roundabouts and for them, the geometric dimensioning and verification must be adapted.

When we talk about Unconventional Roundabouts must be considered both the so-called "new generation roundabouts" (Raindrop or Double Raindrop Roundabouts; Turbo Roundabouts [8] [9]; Two-Geometry Roundabouts [10] [11]), which are currently being built to fulfil safety and performance objectives in cases where classic roundabouts are unable to work well; both the so-called "old roundabouts" which had dimensions and geometries suitable for when precedence was on the branches instead of on the ring (first generation roundabouts) [12]. In Italy, there are many Unconventional Roundabouts of both "typologies", both because in terms of space, there is the need to adopt solutions that are not conventional, and because for the moment there are always obsolete roundabouts on the national territory which have not been adapted and which are often poor in terms of security. Precisely for this last consideration, in this discussion, the authors have decided to take into consideration three Unconventional Roundabouts of the latter type and have decided to analyse them in terms of safety, also because from this point of view there are no in-depth studies for them.

A final introductory consideration concerns the type of accidents that the authors decided to analyse, i.e., rear-end collisions. They are the conflicts/accidents that occur on the entrance branches more frequently at "roundabout" intersections and for this reason, they were chosen as a study parameter.

B. Territorial Framework and O/D Matrices of the Three Identified Roundabouts

This short paragraph lists the three Unconventional Roundabouts analyzed by the authors.

All three roundabouts are situated in Italy, in the Tuscany region and are located in urban areas, therefore the speed referred to during the calculations is equal to 50 km/h [13]. In particular, in Fig. 1, Fig. 2 and Fig. 3, the three aerial images extracted from Google Earth are reported, where the progressive numbers of the branches of the roundabouts are also reported.

Reference is made to them for the reconstruction of the Origin/Destination (O/D) matrices, reported in turn in Table I, Table II and Table III.

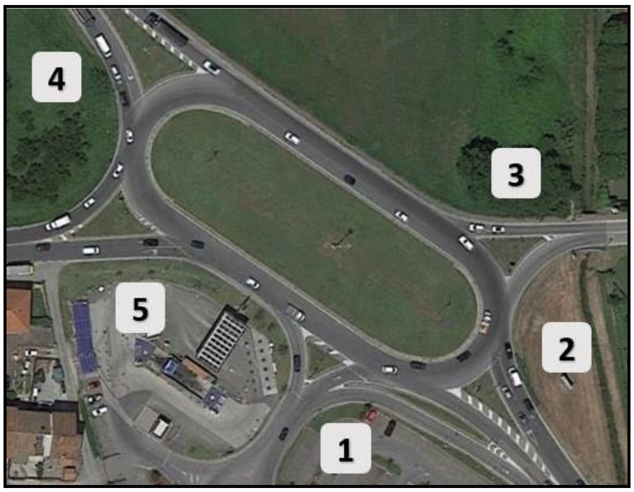

Figure 1. The territorial framework of the 1st Unconventional Roundabout located on SP61-Lucchese-Romana in Lucca, Tuscany, Italy (*source*: Google Earth Pro)

Figure 2. The territorial framework of the 2nd Unconventional Roundabout located on Viale Nazario Sauro in Livorno, Tuscany, Italy (*source*: Google Earth Pro)

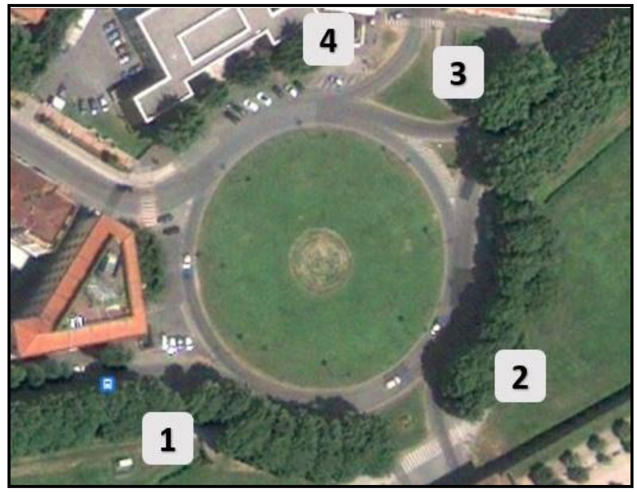

Figure 3. The territorial framework of the 3rd Unconventional Roundabout located on Porta Santa Maria in Lucca, Tuscany, Italy (*source*: Google Earth Pro)

TABLE I. O/D MATRIX OF THE 1ST UNCONVENTIONAL ROUNDABOUT

Roundabout 1 - SP61 Lucchese-Romana (Lucca, Tuscany, Italy)						
Matrice O/D	1	2	3	4	5	TOT
1	0	142	60	36	72	310
2	36	0	140	346	812	1334
3	44	204	0	114	76	438
4	58	320	56	0	280	714
5	58	794	184	372	0	1408
TOT	196	1460	440	868	1240	4204

TABLE II. O/D MATRIX OF THE 2ND UNCONVENTIONAL ROUNDABOUT

Roundabout 2 - Viale Nazario Sauro (Livorno, Tuscany, Italy)				
Matrice O/D	1	2	3	TOT
1	0	390	517	907
2	443	0	691	1134
3	476	541	0	1017
TOT	919	931	1208	3058

TABLE III. O/D MATRIX OF THE 3RD UNCONVENTIONAL ROUNDABOUT

Roundabout 3 - Porta Santa Maria (Lucca, Tuscany, Italy)					
Matrice O/D	1	2	3	4	TOT
1	181	299	1749	0	2229
2	253	0	195	0	448
3	951	52	12	0	1015
4	263	51	12	0	326
TOT	1648	402	1968	0	4018

These matrices were elaborated starting from the data surveys carried out on the three roundabouts through the use of Sony DCR-SX34 digital cameras, positioned at specific points of the intersections, during the peak periods of the week [14].

III. EXISTING ROUNDABOUTS ACCIDENT MODELS

Roundabouts, in general, are considered to be the safest road junctions as they have several advantages including reduction of points of conflict and lower movement and departure speeds. However, accidents can also occur on them and in particular, several studies state that the most common accident that can occur is a rear-end collision. To study the safety characteristics of the elements of the road system, there are several models for predicting accidents [15].

The authors have decided to use in this research two of the most used models, namely those of the Maycock & Hall model and the Arndt & Troutbeck model. They were chosen because they allow the number of accidents to be calculated taking into consideration both the traffic demand, the geometric characteristics of the intersection, and the dynamic ones (such as speed, for example). With these models, it is possible to calculate various types of accidents, but, as explained above, it was decided to use the formulas of the Conflicts Type "Approach" for the Maycock & Hall [4] model (1) and those of the Conflict Types "Rear end" for the Arndt & Troutbeck [5] model (2), which indicate precisely rear-end collisions. Both models make it possible to estimate the number of accidents over a period of time and therefore their unit of measurement is expressed in accidents/years [16].

The two formulas (1) and (2) used are therefore reported below, specifying that the coefficients of these formulas are the standard ones calibrated for conventional roundabouts. In fact, another of the interesting aspects of this research was precisely that of verifying whether these coefficients could also work for Unconventional Roundabouts. To answer this question, see section V.

$$A_2 = 0.0057 \times Q_e^{1.7} \times \exp(20C_e - 0.1e) \quad (1)$$

where:

- Q_e = entering flow, respectively (1000s of vehicles/day);
- C_e = entry curvature [Ce = 1/Re and Re = entry path radius for the shortest vehicle path (m)];
- e = entry width [m].

$$A_r = C_1 \times Q_a^x \times Q_c^y \times S_a^z + C_2 \quad (2)$$

where:

- Q_a = average annual daily traffic (AADT) on the approach;
- Q_c = various AADT flows on the circulating carriageway adjacent to the approach;
- S_a = 85th percentile speed on the approach curve (the potential relative speed between approaching vehicles) [km/h];
- $C_1 = 9.62 \times 10^{-11}$; $C_2 = 0$; x = 1; y = 0.5; z = 2. [5]

IV. SSAM Approach from FHWA

This concise section has been included to define what is meant by surrogate security assessment and how it is possible to carry out such an assessment.

After careful bibliographic research on the surrogate safety measures in safety evaluation and analysis [17], it is possible to affirm that, in any case, whatever safety analysis is a decisive aspect in the evaluation of design choices both for the new road system and for the adaptation of the existing road network.

In fact, several studies deal with safety assessment when any intersection is converted into a roundabout [18] and in addition to this, in the literature, there are also various insights regarding models that connect the parameter "safety of roundabouts" to the predicted speed in them (another fundamental parameter, for example in terms of efficiency estimation) [19].

So, to fulfil this, the Federal Highway Administration (FHWA) has developed and made available the Surrogate Safety Assessment Model (SSAM) program, through which it aims to offer designers, researchers and companies specializing in road design and construction a tool for assessing the safety of an intersection by estimating the frequency of conflicts [20] [21].

The concept of surrogate safety derives from the desire to develop alternative tools to the existing ones to evaluate the accident frequency of road infrastructure (among which mentioned the Empirical Bayesian analysis [22] or the Crash Modification Factors [23]).

While the so-called ordinary methods derive from statistical evaluations based on accidents that have occurred, the surrogate safety methods are instead based on factors that do not require years of accident statistics.

The SSAM program elaborates the trajectory files (.trj files) obtained in output from a dynamic simulation program (in the case of the present research it is decided to use the Aimsun™ program, but in general VISSIM™, TEXAS™, etc..). In detail, SSAM evaluates every single vehicle-vehicle interaction according to criteria with which it can establish whether there is a point of conflict and to which category it belongs. At the end of the computations, SSAM presents the results in tables, allowing the user to filter them according to the parameters of his choice.

As regards the classification of conflicts, the program contemplates four types: Rear end, Lane changing, Crossing and Unclassified.

To classify them, the program evaluates the crossing angle of the trajectories (Fig. 4), if this angle is less than 20° the conflict is of the Rear end type.

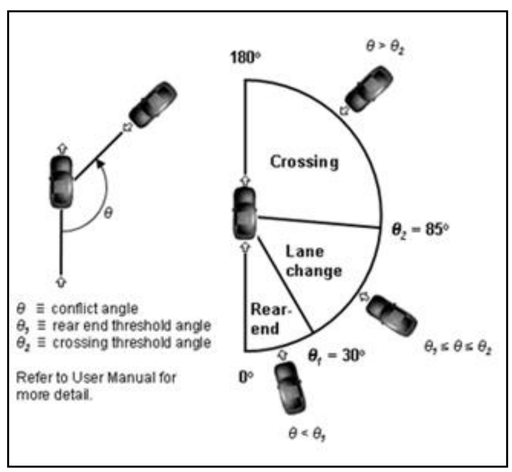

Figure 4. Conflict angle threshold (SSAM)

In the present research, the latter (Rear end) have been taken into consideration, since, as already explained, they are the ones that occur most frequently in roundabout intersections. Their unit of measurement is expressed in conflicts/day.

V. Comparison of the Two Approaches

The following section presents the results of the first and most substantial part of the research, or rather, the comparison between the expected number of accidents calculated through analytical models and the Surrogate Safety Assessment Model (SSAM) of the Federal Highway Administration (FHWA) regarding the three unconventional roundabouts. First of all, a summary table (Table IV) of the calculations carried out is shown which serves to reconstruct the graphs on which most of the considerations will be made.

TABLE IV. Summary table of the Calculations made

Roundabout	Approach	Qe [veh/d]	Arndt & Troutbeck Rear-end [acc/y]	Maycock & Hall Approach [acc/y]	SSAM (TTC = 1.5 s) [conflicts/d]
1	1	3100	0.10	0.07	24
	2	13340	0.28	0.33	383
	3	4380	0.14	0.13	63
	4	7140	0.19	0.23	165
	5	14080	0.29	0.34	207
2	1	9070	0.16	0.15	120
	2	11340	0.20	0.37	203
	3	10170	0.16	0.27	119
3	1	22290	0.18	0.55	160
	2	4480	0.15	0.13	82
	3	10150	0.16	0.32	104
	4	3260	0.09	0.07	36

Furthermore, the authors considered it necessary to also report the explanatory images of the surrogate safety assessment. In detail, the following images (Fig. 5, Fig. 6 and Fig. 7) show an extract of the QGIS software of the three roundabouts, where the points of conflict have been inserted, georeferenced (with TTC = 1.5 s) extracted from the SSAM software after processing the ".trj file", which in turn was obtained from the Aimsun™ simulation software. The Time to Collision (TTC) is one of the SSAM software parameters and expresses the minimum collision time [24]. It can range from an infinite maximum value, when two vehicles never meet, to a minimum value of 0 seconds when an accident occurs. Various studies have been conducted to identify a threshold value of the TTC, such as to separate major accidents from minor and negligible or without consequences accidents [25]. This value, depending on the study, was identified as a fixed value or as the result of a function dependent on the speed or deceleration of the vehicles. The authors have decided to keep the default value of the SSAM program which assumes the value TTC = 1.5 s.

Figure 5. Number of Conflicts obtained by SSAM software and reported on QGIS of 1st Unconventional Roundabout

Figure 6. Number of Conflicts obtained by SSAM software and reported on QGIS of 2nd Unconventional Roundabout

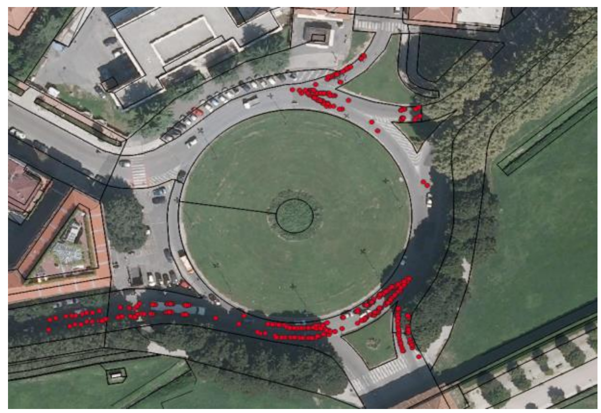

Figure 7. Number of Conflicts obtained by SSAM software and reported on QGIS of 3rd Unconventional Roundabout

Below are the graphs (Fig. 8, Fig. 9 and Fig. 10) which summarize most of the research results. In particular, each graph refers to one of the three roundabouts and is structured as follows: the Q_e (entrance vehicular flow) expressed in vehicles per day is shown on the abscissa axis; while there are two different y axes. The left y-axis is incident models (Arndt & Troutbeck / Maycock & Hall) and is expressed in accidents per year, while the right is the SSAM results and is expressed in conflicts per day.

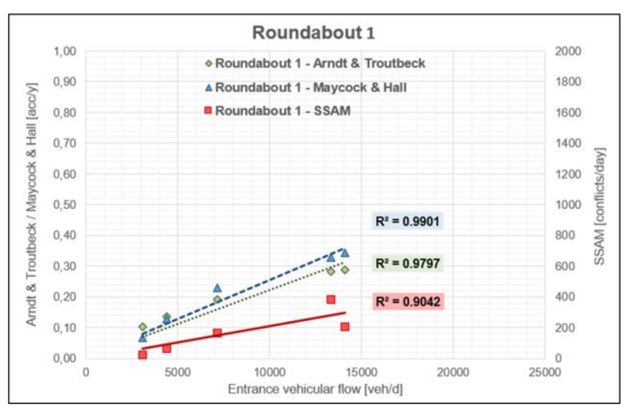

Figure 8. Graph of Results for the 1st Unconventional Roundabout

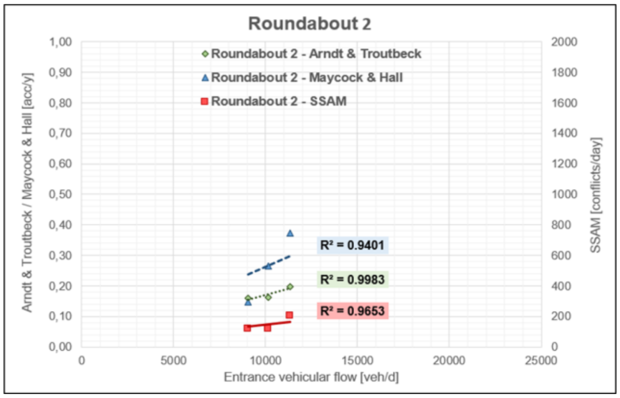

Figure 9. Graph of Results for the 2nd Unconventional Roundabout

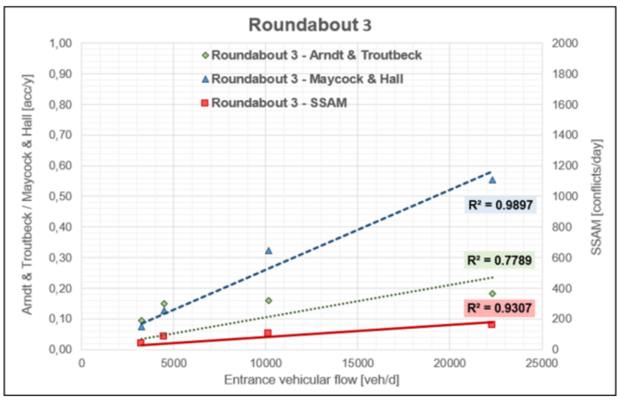

Figure 10. Graph of Results for the 3rd Unconventional Roundabout

On the graphs, as many points have been reported as there are entrance arms of the roundabout in question and a linear trend line passing through the origin (0; 0) has then been created for them.

After that, the authors decided to calculate the coefficient of determination R^2 for each trend line. It is a statistical value that allows us to understand whether a linear regression model can be used to make predictions. Its value is always between 0 and 1, or between 0% and 100% if you want to express it in percentage terms. $R^2 = 0$ indicates a model whose predictor variables do not explain the variability of y around its mean at all. $R^2 = 1$ indicates a model whose independent variables fully explain the variability of y around its mean; that is, knowing the values of the independent variables one can predict exactly what the value of y will be. Clearly, the values 0 and 1 are limit values, what emerges is that the greater the value of R^2, the more the model has high predictive power, i.e., the better the ability of the explanatory variables to predict the values of the dependent variable. Usually, we talk about high R^2 values, when they are higher than 0.7.

At this point, after having explained the type of graphs used and the reference values, it is possible to go into detail on the considerations relating to the actual results. For all the graphs, i.e., for all the roundabouts, the R^2 values are generally excellent (they are always higher than 0.9, except for one case), both as regards the accident models and as regards the values of the conflicts obtained with SSAM.

This is an excellent result as the three roundabouts to which the models have been applied are Unconventional Roundabouts, i.e., "different" intersections from the ones on which the models have been calibrated. Therefore, as a first result, it is certainly possible to state that the accident models used (Arndt & Troutbeck / Maycock & Hall), which are already valid and validated for conventional roundabouts, can also be used for Unconventional Roundabouts, using the same formulations and the same coefficients.

Also, about the SSAM results, the R^2 values are always higher than 0.9 and despite the different scales it is possible to state that the trend of the trend lines of the points deriving from SSAM is very similar to that relating to the accident models.

This is therefore another excellent result that the authors have arrived at, namely that even for Unconventional Roundabouts there is a correspondence between the accident models and the calculation of the conflicts carried out with SSAM.

Finally, the authors also noted a further fact regarding Fig. 10, i.e., the graph referring to roundabout number 3. The trend line of the Arndt & Troutbeck model has an R^2 that is always acceptable, but clearly lower than all the others (0.7789).

The explanation that the authors came up with is the following: roundabout number 3, in addition to being of an unconventional type, is also atypical from the point of view of the approaches, since, as can be seen from the territorial framework (Fig. 3) and the corresponding O/D matrix (Table III), the approach 4 is formed only by the input branch and not the output branch.

This, together with the particular geometry of the roundabout, has led to a high difference between the incoming flow rate Q_e and the circulating flow rate Q_c of the adjacent approach 1 (this difference is underlined in Table V). So, another result that the authors have reached is the consideration that the model of Arndt & Troutbeck does not adapt perfectly to Unconventional Roundabouts in which there is, for some branches, a high difference between the incoming flows and circulating flows.

TABLE V. EXTRACT FROM THE CALCULATION TABLE, WHERE THE DIFFERENCE BETWEEN QE AND QC CAN BE SEEN

Roundabout	Approach	Qe [veh/d]	Qc [veh/d]	Delta (Qe-Qc/Qc)
3	1	22290	1150	18.38
	2	4480	19540	0.77
	3	10150	4340	1.34
	4	3260	14490	0.78

A final comparison was also made for the three Unconventional Roundabouts as a whole.

In fact, a last graph (Fig. 11), of the same typology as the previous ones, was constructed however by taking into consideration the roundabouts as a whole and no longer approach by approach. In this way, it was possible to compare the three roundabouts on a single graph and this led to the following consideration.

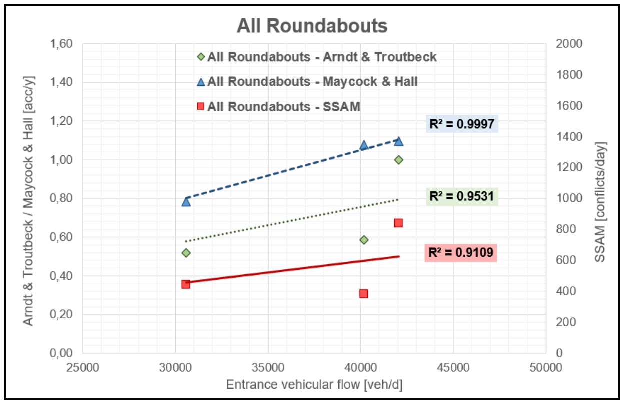

Figure 11. Graph of Results for the three Unconventional Roundabouts together

The values of R^2 are excellent and also the roundabout 3 which had a deficit on the Arndt & Troutbeck model due to the difference between the incoming flows and the circulating flows at one of the approaches, if it is considered as a whole, it is possible to homogenize with the other results.

VI. Focused Application of SSAM Approach to Real Case Studies

This last paragraph before the conclusions of the entire work, deals with the second part of the research and focuses on the SSAM application used for two real case studies for which, thanks to the results obtained, it was possible to demonstrate the effectiveness of the proposed solutions. This idea was developed starting from one of the conclusions set out in the previous paragraph, where the comparison was made between SSAM and Accident Models, i.e., that even for Unconventional Roundabouts there is a correspondence between the two methods. Thanks to this consideration, it was therefore, possible to use the SSAM model for two real cases, for which the accident models were not very suitable or difficult to apply. It should also be said that all this is further strengthened by bibliographic research, in which it was found that there already exist several studies on the application of SSAM to real cases [26] [27]. Starting from the considerations just made, the two real cases that have been analysed are the following: an Unconventional Roundabout (and in particular a Double Raindrop Roundabout); a Motorway Tollbooth (and in particular the intermediate section which is located between two successive motorway toll booths where various weaving manoeuvres take place). For both real case studies, two solutions will be illustrated. The so-called "Initial Solution" will concern either the current state of the intersection (in the case of the motorway toll booth) or a possible solution proposed for the intersection itself, which however was not found to be safe and efficient enough (in the case of the unconventional roundabout); and the so-called "Project Solution" which instead will concern a proposed design hypothesis for the intersection. For both solutions, a dynamic simulation was carried out with the aforementioned Aimsun™ software which made it possible to obtain the necessary inputs (trajectory files) for the surrogate safety assessment carried out via SSAM. There will now follow two paragraphs relating to the two real cases in which they have been inserted: the territorial framework of the intersection, the traffic status of the intersection, the number of conflicts obtained with SSAM and reported on QGIS for both the "Initial Solution" and the "Project Solution", a final comparison between the two solutions.

A. *Real Case Study 1: Unconventional Roundabout in Lucca, Tuscany, Italy*

The first real case study that will be covered is an Unconventional Roundabout located in Lucca, Tuscany, Italy. The roundabout falls into the category of Unconventional Roundabouts as both the shape of its "Initial Solution" and that of its "Project Solution" are certainly outside conventional geometric standards. If we wanted to classify it, we could include it among the Raindrop or Double Raindrop Roundabouts. This type of work is also supported by the fact that studies have already been done regarding the application of SSAM to real cases of Unconventional Roundabouts, such as those relating to the Separated Central Island (SCI) Roundabouts [28]. Having made this brief introduction, it is now possible to move on to illustrate the real case study 1 starting from the images of the territorial framework of the "Initial Solution" and the "Project Solution" (Fig. 12 and Fig. 13) and continuing with the O/D matrices always relating to the two solutions (Table VI and Table VII).

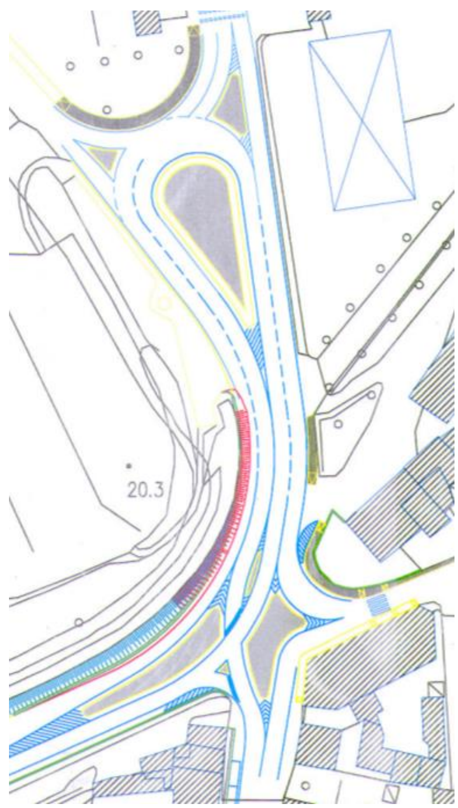

Figure 12. Territorial framework of the Unconventional Roundabout located in Lucca, Tuscany, Italy ("Initial Solution")

The "Initial Solution" (Fig. 12) is composed of a very complex at-grade intersection in the southern part and a raindrop roundabout in the northern part.

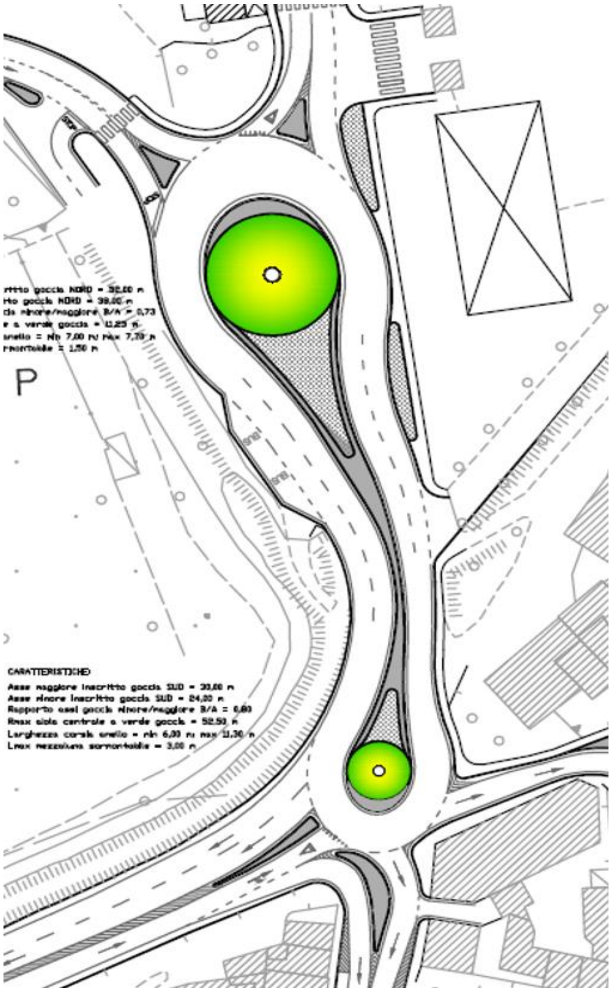

Figure 13. Territorial framework of the Unconventional Roundabout located in Lucca, Tuscany, Italy ("Project Solution")

The "Project Solution" (Fig. 13) is composed of a double raindrop roundabout. The two O/D matrices (Table VI and Table VII) refer to the arms of the intersections and are numbered from 1 to 4 starting from the North and continuing counter clockwise (therefore: N = 1, W = 2, S = 3 and E = 4).

TABLE VI. O/D MATRIX OF THE UNCONVENTIONAL ROUNDABOUT ("INITIAL SOLUTION")

O/D Matrix	1	2	3	4	Qe
1	0	439	1160	0	1599
2	482	0	66	0	548
3	0	0	0	0	0
4	502	488	25	0	1015
Qu	984	927	1257	0	3162

TABLE VII. O/D MATRIX OF THE 3RD UNCONVENTIONAL ROUNDABOUT ("PROJECT SOLUTION")

O/D Matrix	1	2	3	4	Qe
1	0	327	864	1164	2355
2	605	0	17	185	807
3	0	0	0	0	0
4	0	0	0	0	0
Qu	605	327	881	1349	3162

These matrices were elaborated starting from the data surveys carried out on the intersection, during the peak periods of the week.

At this point, as was done for paragraph V, the authors deemed it necessary to report the explanatory images of the surrogate safety evaluation of the Unconventional Roundabout of Lucca, both in its "Initial Solution" and "Project Solution" configuration. In detail, the following images (Fig. 14 and Fig. 15) show an extract from the QGIS software of the two solutions, where the conflict points were inserted, georeferenced (with TTC = 1.5 s) extracted from the SSAM software after having processed the ".trj file", which in turn was obtained from the Aimsun™ simulation software.

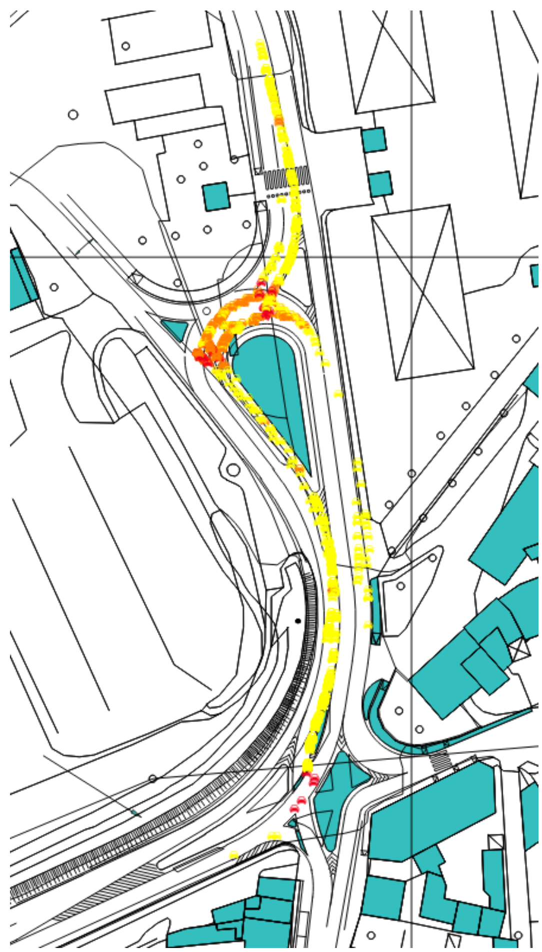

Figure 14. Number of Conflicts obtained by SSAM software and reported on QGIS of the Unconventional Roundabout ("Initial Solution")

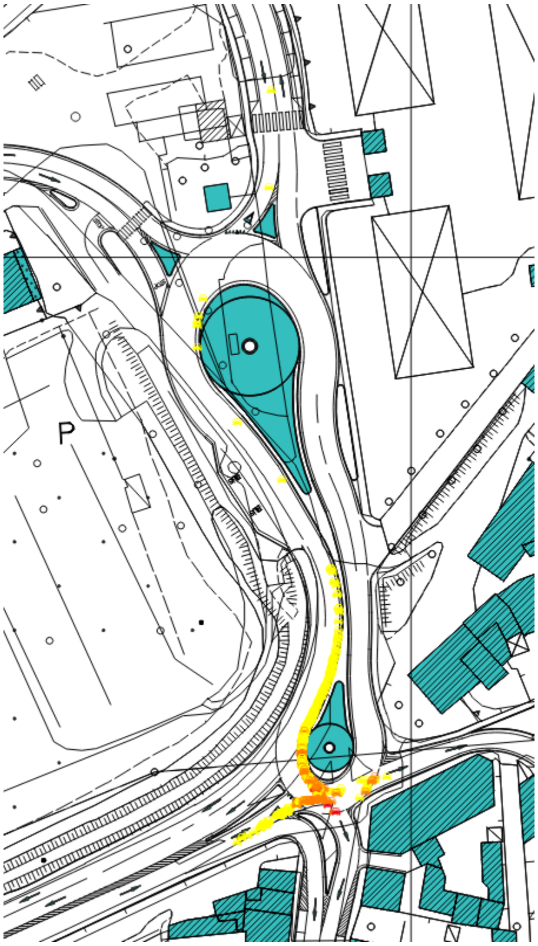

Figure 15. Number of Conflicts obtained by SSAM software and reported on QGIS of the Unconventional Roundabout ("Project Solution")

It is specified that in this case, you can also notice the difference between the various types of conflicts (listed and explained in Fig. 4) and in detail: in red there are Crossing type conflicts, in orange there are Lane change type conflicts and finally those of the Rear end type in yellow.

Before concluding the paragraph, it is also appropriate to insert the summary table (Table VIII) of the number of conflicts calculated with SSAM of the two solutions which served to compare them and demonstrate that, thanks to the results obtained, the "Project Solution" was better from the point of view of safety.

TABLE VIII. SUMMARY TABLE OF THE COMPARISON

SSAM Calculation					
TTC = 1.5 s					
"Initial Solution"		"Project Solution"		Comparison %	
Unclassified	0	Unclassified	0	Unclassified	-
Crossing	69	Crossing	46	Crossing	-33%
Lane Change	383	Lane Change	805	Lane Change	110%
Rear End	1015	Rear End	996	Rear End	-2%
Total	1467	Total	1847	Total	26%
TTC = 0 s					
"Initial Solution"		"Project Solution"		Comparison %	
Unclassified	0	Unclassified	0	Unclassified	-
Crossing	34	Crossing	0	Crossing	-100%
Lane Change	202	Lane Change	22	Lane Change	-89%
Rear End	32	Rear End	30	Rear End	-6%
Total	268	Total	52	Total	-81%

From this table, it is possible to immediately notice that regarding the TTC = 0 s (which is the theoretical minimum value to be assigned to evaluate the conflicts that "certainly" will occur) there is a very high decrease for each type of conflict, up to a total decrease of -81%. However, regarding the TTC = 1.5 s (default value), one fundamental thing can be noted, namely that even if there is an increase in the "lane change" type conflict points, there is a clear decrease in the crossing type conflicts which are the most dangerous (with an angle of incidence between 85° and 180°, see Fig. 4).

Therefore, thanks to this type of analysis, it is possible to state that from the point of view of security analysis, the "Project Solution" is better.

B. Real Case Study 2: Motorway Tollbooth in Lucca, Tuscany, Italy

The second real case study that will be illustrated is a highway toll booth located in Lucca, Tuscany, Italy. First of all, is important to affirm that also this type of work is supported by the fact that previous research has already been carried out regarding the micro-simulation of real cases of motorway toll booths [29], even if without the specific application of SSAM.

Therefore, this in-depth study constitutes a further innovative aspect of the research; that said, it is now possible to move on to illustrate the real case study. To be more precise, the simulations that were carried out concerned the two motorway toll booths in the city of Lucca (West and East) which are located at a very close distance, as is illustrated in the territorial framework (Fig. 16).

Figure 16. The territorial framework of the Motorway Tollbooth in Lucca, Tuscany, Italy
(*source*: Google Earth Pro)

In fact, the study began from the consideration that due to the close distance between the entrance from the Lucca West motorway toll booth and the exit from the Lucca East motorway toll booth, several weaving manoeuvres occur (dangerous manoeuvres especially at high speed). Consequently, the project was aimed at moving the Lucca East toll booth and transforming it into an exchange car park.

Without going into the details of the work, what interests the authors is the fact that one of the main factors that made it possible to demonstrate that this design idea was correct, were precisely the dynamic simulations and the SSAM application in the two situations (the "Initial Situation" with the toll booths at the current state and the "Project Situation" with the moving of the Lucca East toll booth and its transformation into an exchange parking lot). The results of the application of SSAM are therefore reported below.

As already mentioned in Fig. 16 the territorial framework has been inserted, while in the subsequent figures (Fig. 17 and Fig. 18) there are explanatory images of the surrogate safety assessment in the intermediate road sections between the two toll booths, where takes place the weaving manoeuvres. In particular, the following two images show the extracts from the QGIS software of the two situations, where the conflict points were inserted, georeferenced (with TTC = 1.5 s) extracted from the SSAM software after having processed the ". trj file", which in turn was obtained from the Aimsun simulation software.

The figures, as already mentioned, refer to the "Initial Situation" corresponding to the reality in which there are two motorway toll booths very close to each other, and to the "Project Situation" in which the Lucca East toll booth has been transformed into an interchange car park.

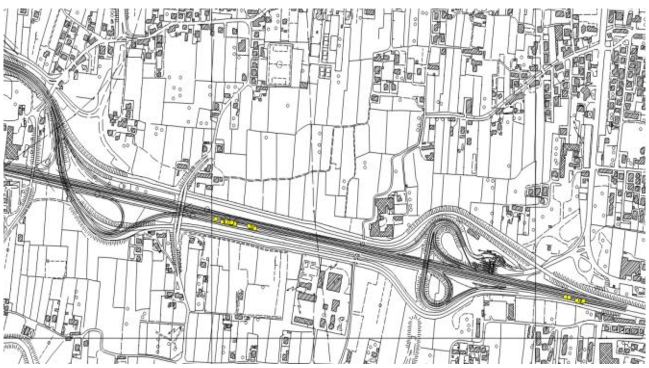

Figure 17. Number of Conflicts obtained by SSAM software and reported on QGIS of the Motorway Tollbooth ("Initial Situation")

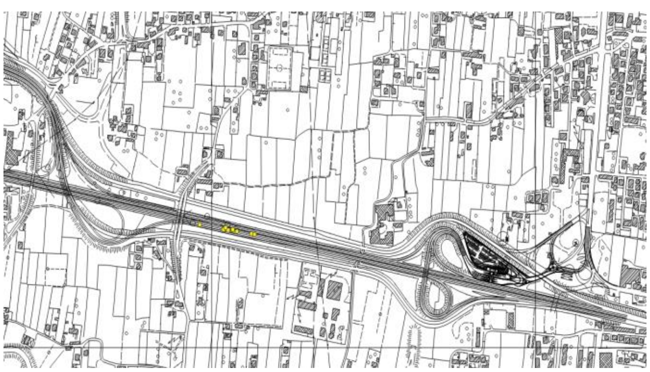

Figure 18. Number of Conflicts obtained by SSAM software and reported on QGIS of the Motorway Tollbooth ("Project Situation")

Before concluding the paragraph, as was done for the previous paragraph, it is also appropriate to insert the summary table (Table IX) of the number of conflicts calculated with SSAM of the two situations which served to compare them and demonstrate that, thanks to the results obtained, the "Project Situation" was better from the point of view of safety.

TABLE IX. SUMMARY TABLE OF THE COMPARISON

SSAM Calculation					
TTC = 1.5 s					
"Initial Situation"		"Project Situation"		Comparison %	
Unclassified	0	Unclassified	0	Unclassified	0%
Crossing	0	Crossing	0	Crossing	0%
Lane Change	0	Lane Change	0	Lane Change	0%
Rear End	30	Rear End	15	Rear End	-50%
Total	30	Total	15	Total	-50%

From this table it is possible to notice that at the Lucca West motorway toll booth, there is a reduction in the number of possible conflicts due to the movement of vehicular flows, directed towards the eastern part of the city of Lucca, towards the new toll booth moved further forward; which also involves a reduction in weaving manoeuvres along the stretch. In addition, the Lucca East motorway toll booth, transformed into a motorway interchange car park, has observed a cancellation of the possible conflicts in entry and exit to and from it, due to the change of destination of the same and consequently to the lower vehicle flows circulating there. Concluding, in terms of the number of possible conflicts that can occur on the stretch in question, an overall reduction of 50% is observed. Therefore, thanks to this type of analysis, it is possible to state that from the point of view of security analysis, the "Project Situation" is better.

VII. CONCLUSIONS AND FUTURE RESEARCH WORK

First of all, it is worth remembering that this article is an extended version of the conference paper "Comparison between Surrogate Safety Assessment Models (SSAM) and Accident Models on Unconventional Roundabouts" [1], presented at the Twelfth International Conference on Data Analytics in September 2023.

In the first and most in-depth part, this article describes the comparison between the Federal Highway Administration (FHWA) Surrogate Safety Assessment Model (SSAM) and the predicted number of accidents calculated using the Arndt & Troutbeck and Maycock & Hall analytical models, as concern the Unconventional Roundabouts [30] [31]. In the second part instead, in which most of the new contents were inserted, a focus on the SSAM application, employed for two real case studies, has been illustrated.

The conclusions relating to the first part will now be illustrated first. Three Unconventional Roundabouts located on the Italian territory that have different shapes and sizes from the regulatory standards were analysed. Other works and articles have been published regarding the comparison between the models mentioned, however, the novelty of this research proposed by the authors lies precisely in the different base data, i.e., the Unconventional Roundabouts. The type of accident and conflict chosen for the comparison made is that of rear-end collisions, as it is the most common present on roundabout intersections. In the sections of the article, various initial considerations follow one another which deepen the concepts of Unconventional Roundabouts, surrogate safety analysis models (SSAM) and accident models; up to section V where the results of the entire research were clearly explained.

Summarizing these results, the authors found that: 1) the accident models used (Arndt & Troutbeck / Maycock & Hall) already valid and validated for conventional roundabouts, can also be used for Unconventional Roundabouts, using the same formulations and the same coefficients also because a certain correspondence was also found between them in terms of the number of accidents per year; 2) also for Unconventional Roundabouts there is a correspondence between the accident models and the calculation of the conflicts carried out with SSAM; 3) Arndt & Troutbeck model is not perfectly suited to Unconventional Roundabouts in which there is, for one or more branches, too high a difference between incoming flows and circulating flows.

As previously said, the extended part of this work instead concerned a focus on SSAM application, employed for studying two real case studies. This idea was developed starting from the conclusion 2) illustrated above, i.e., that also for Unconventional Roundabouts there is a correspondence between the accident models and the calculation of the conflicts carried out with SSAM. Thanks to this consideration, it was therefore possible to apply the SSAM model to two real cases for which a safety analysis was required. In detail, the first real case was an Unconventional Roundabout (classified as Raindrop or Double Raindrop Roundabout) located in Lucca, Tuscany, Italy; was associated with the Unconventional Roundabouts because its shape in both the "Initial Solution" and the "Design Solution" was certainly outside conventional geometric standards. Instead, the second real case was a highway tollbooth located in Lucca, Tuscany, Italy; to be more specific, the research work that was carried out concerned the two motorway toll booths of Lucca West and Lucca East which are located at very close distance.

The conclusions that can be drawn from the study of these two real cases are the same, that is, thanks to this type of analysis it is possible to state that from the point of view of security analysis, one of the two solutions (and in these two specific cases, the project ones) is better than the other.

Speaking even more generally and therefore taking up the entire article, it is possible to state that the Surrogate Safety Assessment Model (SSAM) is a very powerful tool that can be used on various occasions both for research and practical purposes. The Accident Models however remain usable on all those occasions in which the starting conditions exist to be able to apply them (such as for conventional roundabouts), but in all those cases in which these models have not been validated and/or calibrated, SSAM remains one of the best solutions for evaluating intersection safety.

As previously mentioned in the introduction, it is important to clarify that this paper presents an exploratory study and, as such, the authors do not aim to propose any specific model. The primary objective of this paper is to describe empirical evidence derived from a small sample of Unconventional Roundabouts; this aspect is emphasized throughout the entirety of the paper.

Nevertheless, despite being only a preliminary exploration, the implications of the present study are significant as they lay the groundwork for future developments that could potentially redefine the approach to computational modelling of Unconventional Roundabout safety.

About that, before concluding the work, the authors decided to also propose some ideas for the possible future development of this research. First of all, this work can certainly be expanded by analysing further case studies and thus obtaining more points to use on the graphs obtained. Furthermore, the accident models utilised were used in the first analysis without the recalibration for the Unconventional Roundabouts; therefore another next step could be proper to go and search for the actual accident data and thus verify whether the parameters used can be further improved and better recalibrated for Unconventional Roundabouts (it is emphasized that however, as explained in section V, the accident models used, can already be used also for Unconventional Roundabouts, given the statistical results obtained by the authors).

REFERENCES

[1] A. Pratelli, L. Brocchini, P. Leandri, and R. Aiello, “Comparison between Surrogate Safety Assessment Models (SSAM) and Accident Models on Unconventional Roundabouts”, Proceedings of the Twelfth International Conference on Data Analytics, IARIA, ThinkMind, Porto, pp. 7-12, 2023.

[2] L. Vasconcelos, L. Neto, A. M. Seco, and A. B. Silva, “Validation of the Surrogate Safety Assessment Model for Assessment of Intersection Safety”, Transportation Research Board, No. 2432, pp. 1-9, Washington, D.C., 2014.

[3] Italian Ministry of Infrastructures & Transport, “Norme funzionali e geometriche per la costruzione delle intersezioni stradali”, DM n. 1699 of 19/04/2006, Rome, 2006.

[4] G. Maycock and R. D. Hall, “Accidents at four-arm roundabouts”, PTRC Summer Annual Conference, Brighton, United Kingdom, 1984.

[5] O. K. Arndt and R. J. Troutbeck, “Relationship Between Roundabout Geometry and Accident Rates”, Transportation research circular, 1998.

[6] M. S. Ghanim and K. Shaaban, “A Case Study for Surrogate Safety Assessment Model in Predicting Real-Life Conflicts”, Arabian Journal for Science and Engineering, Vol. 44 pp. 4225-4231, 2019.

[7] T. Tollazzi, “Alternative Types of Roundabouts. An informational guide”. Springer, Berlin, Germany, 2015.

[8] A. B. Silva, L. Vasconcelos, and S. Santos, “Moving from Conventional Roundabouts to Turbo-Roundabouts”, EWGT2013 – 16th Meeting of the EURO Working Group on Transportation. Procedia - Social and Behavioral Sciences, Vol. 111, pp. 137-146, 2014.

[9] G. Tesoriere, T. Campisi, A. Canale, and T. Zgrablić, “The Surrogate Safety Appraisal of the Unconventional Elliptical and Turbo Roundabouts”, Journal of Advanced Transportation, pp. 1-9, 2018.

[10] A. Pratelli, R. R. Souleyrette, and L. Brocchini, “Two-Geometry Roundabouts: Design Principles”, Transportation Research Procedia, Vol. 64, pp. 299-307, 2022.

[11] A. Pratelli and L. Brocchini, “Two-Geometry Roundabouts: Estimation of Capacity”, Transportation Research Procedia, Vol. 64, pp. 232-239, 2022.

[12] A. R. Alozi and M. Hussein, “Multi-criteria comparative assessment of unconventional roundabout designs”, International Journal of Transportation Science and Technology, Vol. 11, pp. 158-173, 2022.

[13] D. Ciampa, M. Diomedi, F. Giglio, S. Olita, U. Petruccelli, and C. Restaino, “Effectiveness of unconventional roundabouts in the design of suburban intersections”, European Trasnport, Vol. 80, 2020.

[14] A. Pratelli, P. Sechi, and R. R. Souleyrette, “Upgrading Traffic Circles to Modern Roundabouts to improve Safety and Efficiency – Case Studies from Italy”, Promet – Traffic&Transportation, Vol. 30, No. 2, pp. 217-229, 2018.

[15] A. P. Tarko, “Use of crash surrogates and exceedance statistics to estimate road safety”, Accident; Analysis and P revention, Vol. 45, pp. 230-240, 2012.

[16] S. Daniels, T. Brijs, E. Nuyts, and G. Wets, “Extended prediction models for crashes at roundabouts”, Safety Science - SAF SCI, Vol. 49, pp. 198-207, 2011.

[17] D. Singh and P. Das, “A Review on Surrogate Safety Measures in Safety Evaluation and Analysis”, 6th Conference of the Transportation Research Group of India, Lecture Notes in Civil Engineering, Vol. 273, pp. 113-129, 2021.

[18] B. N. Persaud, R. A. Retting, P. E. Garder, and D. Lord, “Safety Effect of Roundabout Conversions in the United States: Empirical Bayes Observational Before-After Study”, Transportation Research Record, Vol. 1751, pp. 1-8, 2001.

[19] Y. Chen, B. Persaud, E. Sacchi, and M. Bassani, “Investigation of models for relating roundabout safety to predicted speed”, Accident Analysis and Prevention, Vol. 50, pp. 196-203, 2013.

[20] D. Gettman, “Surrogate Safety Measures from Traffic Simulation Models”, Transportation Research Record Journal of the Transportation Research Board, No. 1840, 2003.

[21] O. Giuffrè, A. Grana, M. L. Tumminello, T. Giuffrè, and S. Trubia, “Surrogate Measures of Safety at Roundabouts in AIMSUN and VISSIM Environment”, 15th Scientific and Technical Conference Transport, Katowice, Poland, 2018.

[22] M. de Lapparent, “Empirical Bayesian analysis of accident severity for motorcyclists in large French urban areas”, Accident Analysis and Prevention, Vol. 38, pp. 260-268, 2006.

[23] B. Persaud, T. Saleem, M. E. Granados, T. Rajeswaran, “Can crash modification factors be estimated from surrogate measures of safety?”, Advances in Transportation Studies, Vol. 1 pp. 149-162, 2018.

[24] A. Abdelhalim and M. Abbas, “An Assessment of Safety-Based Driver Behavior Modeling in Microscopic Simulation Utilizing Real-Time Vehicle Trajectories”, 2022.

[25] A. Pratelli, L. Brocchini, and N. Francesconi, “Estimating and Updating Gap Acceptance Parameters for Hcm6th Roundabout Capacity Model Applications”, WIT Transactions on Ecology and the Environment, Vol. 253, pp. 477-486, 2021.

[26] D. Muley, M. Ghanim, and M. Kharbeche, “Prediction of Traffic Conflicts at Signalized Intersections using SSAM”, Procedia Computer Science, Vol. 130, pp. 255-262, 2018.

[27] M. S. Ghanim and K. Shaaban, “A Case Study for Surrogate Safety Assessment Model in Predicting Real-Life Conflicts”, Arabian Journal for Science and Engineering, Vol. 44, pp. 4225-4231, 2019.

[28] M. Hasanvand, A. S. A. Nasiri, O. Rahmani, K. Shaaban, and H. Samadi, “A Conflict-Based Safety Diagnosis of SCI Roundabouts Using a Surrogate Safety Measure Model”, Sustainability, Vol. 15, 2023.

[29] G. Aksoy, H. B. Celikoglu, and E. Gedizlioglu, “Analysis of toll queues by micro-simulation: results from a case study in Istanbul”, Procedia – Social and Behavioral Sciences, Vol. 111, pp. 614-623, 2014.

[30] TRB, “Roundabouts: An Informational Guide - Second Edition”. Washington, D.C.: The National, 2010.

[31] TRB, “Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis”, Washington, D.C.: The National, 2016.