Accident Phenomenology Valuation at Circular Intersections. Probabilistic Approach to Case Studies in Urban Area

Granà A.
Researcher – D.I.I.V. – Dipartimento di Ingegneria delle Infrastrutture Viarie - Università di Palermo

Giuffrè T.
PhD student - DIIAR – Sez. Infrastrutture Viarie - Politecnico di Milano

SYNOPSIS

Knowledge relating to traffic safety at roundabouts is not an exhaustive reference for geometric design when there are organizational schemes for intersections characterized by physical constraints that render it necessary to make “compromise choices” relating to one or more geometric features of the roundabout (“Roundabout Inspired Intersections” – RI intersections).
Based on these considerations, in a previous research (Granà, 2002), a detailed accident analysis of a statistically significant sample of such intersections has been developed; it made possible to deduce the levels of responsibility of the different accident-causing factors in determining the risk of accidents and to evaluate road use safety as a function of the systemic characteristics of the intersection.
The results of this analysis are the starting point for the research presented in this paper. The objective of this study is, in particular, to identify and to value possible correlations between crash rates and specific geometric characteristics for RI intersections.
The nature and characteristics of the data sample suggested exploring the potentiality of fuzzy logic methods to explain the accident phenomenon relating to RI intersections; the present study, from the methodological viewpoint, underlines the possibility of using probabilistic methods based on fuzzy mathematics for interpreting the accident phenomenon and for trying to generalize the results of the accident analysis.
The results obtained on case studies made up of a sample of 34 RI intersections are an example of the types of information obtainable by means of the proposed approach on accident-causing factors for the particular type of intersections.

Accident Phenomenology Valuation at Circular Intersections. Probabilistic Approach to Case Studies in Urban Area

INTRODUCTION

According to the current definition, roundabouts are circular intersection systems made up of a central area that is totally or partially inaccessible to users, surrounded by a priority ring, in which traffic can go round in an anticlockwise direction from two or more entries.
This particular traffic regulation system, together with a geometrical design characterized by curved lines or specific design requisites (central island shape, circulatory roadway width, symmetry and number of the arms, entry width, etc), cause a reduction in speed which on the circulatory roadway typically goes down to less than 30 mph.
Modern roundabouts incorporate approach curvature to slow entering traffic to a safe speed; for this reason, particularly in urban areas, one of the benefits of roundabout installation is the improvement in overall safety. Nevertheless, it is only during the last twenty years that the use of roundabouts has received increased attention by both the public and road infrastructure engineering professionals.
The design methods of this kind of intersection, including the right of way for the circulating traffic, have been refined through some changes in the course of time. In this connection we can note: i) the tendency to reduce the size of the roundabout; ii) the generalization of the conversion from the old priority rule (give way to entering vehicles) to off-side priority (give way to circulating vehicles)[1].
The coexistence in a lot of Italian cities of roundabouts operating with the off-side priority rule for circulating traffic ("the French system") and with the old priority rule for entering traffic, both with the same validity, causes safety problems for road traffic. Because of what was said above, roundabouts have to be considered to have proper standards compared to other intersection forms (conventional intersections), so that the design of new roundabouts, or the conversion of selected sites into roundabouts to replace problem intersections, would be a kind of infrastructural project suited to ensuring safety.
Circular intersections also include organizational schemes for junctions characterized by a geometric design similar to roundabouts but resulting from compromise choices relating to one or more geometric features of the roundabout (central island shape, circulatory roadway width, symmetry and number of arms, entry width, etc). For this kind of intersection specific safety problems are found, particularly in urban areas, because of the different existing constraints and the great variety of configurations they take on.
The aim of this research is to help to account for the accident phenomenology of this kind of road scheme; the intersections examined in this research are referred to as "roundabout inspired intersections" (RI intersections), in order to distinguish them from typical roundabouts.
The analysis of several case studies in urban area, extracted from the road network in Palermo, was the starting point of this research. Each single intersection in the sample was characterized regarding operational performances (different traffic conditions, bad functioning in specific traffic situations, etc.) and then subjected to a safety analysis, correlated to specific geometric features and accidents which have effectively occurred.
The explanation of the main phases of the research, the methodological approach applied and the results obtained are preceded by a review of the main international accident studies with regard to urban areas, in order to study in detail the accident phenomenology at this kind of intersection and to understand better the reasons for the increased safety level at traditional roundabouts.

INTERNATIONAL ACCIDENT STUDIES

The benefits resulting from roundabout installation, as an alternative to or replacement for other intersection forms, become clearly stated considering the results of international accident studies (also including before-and-after studies); the most relevant are listed as follows.
A precursory study of this kind was carried out by Maycock and Hall (Maycock and Hall, 1984). In 1984 they studied personal injury accidents at a sample of 84 four-arm roundabouts on main roads in the UK; the roundabout types examined included small roundabouts, conventional roundabouts and two-lane roundabouts. Their main findings were:

- in large and medium roundabouts, the crash risk (the average accident frequency and the average accident rate) is less than in small roundabouts. For the first ones, in fact, Maycock and Hall report an average accident frequency equal to 3.31 personal injury accidents per year (16 percent of which were classed as fatal or serious) and the average accident rate equal to 27.5 accidents per 100 million vehicles passing through the intersections[2];
- the analysis by accident type (entering-circulating accidents, approaching accidents, single-vehicle accidents and other accidents) showed that the accidents at conventional roundabouts were relatively evenly divided; by contrast, at small roundabouts more than two-thirds of accidents were of the entering-circulating type;
- the risk of accidents in roundabout for two-wheel riders is much more considerably superior than cars; pedestrian accidents represented about 4-6 percent of all accidents in this sample of roundabouts.

The generalized linear regression model proposed by Maycock and Hall to analyze the correlations between accidents by accident type (accidents per year per arm), traffic flows (car and pedestrian flows) and roundabout geometry gave very interesting results that have significantly influenced all accident studies carried out since.

According to a further English study (Ourston and Doctors, 1995), based on the examination of about 258,000 personal injury accidents that occurred in the UK, only 5.5 percent of all intersection accidents (0.43 percent of which were classed as fatal accidents) occurred at roundabouts.

An Australian accident study (Tudge, 1990), based on the examination of accident data from 1981 to 1987 at 290 intersections (230 roundabouts and 60 controlled intersections in New South Wales, Australia), highlighted the fact that there was a 50 percent overall reduction in accidents at roundabouts with a 63 percent reduction in fatal accidents, a 45 percent reduction in injury accidents and a 40 percent reduction in damage-only accidents.

An accident analysis was carried out in Germany (Stuwe, 1991) through a comparative study between 14 roundabouts and 14 other controlled intersections, characterized by similar conditions regarding traffic parameters such as traffic volume and driver behaviour. The accident data analysis showed that the total number of accidents at roundabouts was higher than at other intersections (possibly with regard to the scanty familiarity of road users with roundabouts of recent installation), but the severity of these accidents was lower.

Table 1 shows a comparison of accident rates for two groups of roundabouts (different in time of installation) and other controlled intersections, characterized by different traffic control systems. Specifically, the two distinct categories of roundabouts are:
- roundabouts with an old design, with two-lane entries and with small entry angles (angle of potential conflict between circulating and entering flows). These intersections had a high number of accidents;
- modern single-lane roundabouts, with almost radial entrances and 92÷116 ft (28÷35 m) inscribed circle diameter; these roundabouts had few accidents.

Table 1: Accident rate

	Accident Rate (accidents per 1 million vehicles)	
	Roundabouts	Intersections
Older roundabouts/intersections with traffic signal	6,58	3,35
Newer roundabouts/intersections with traffic signal	1,24	1,00
All roundabouts/all intersections	4,40	2,76

For three sites rebuilt into roundabouts (these three roundabouts had diameters between 28 and 35 m), Stuwe conducted a before-and-after study and, although the sample size was too small to allow for statistically significant results, highlighted (see Figures 1 and 2) the considerable reduction of the number of accidents (from 4 accidents per year to 2.4 accidents per year) and the number of personal injury accidents (from 3.3 injuries per year to 0.5 injuries).

Further accident studies were carried out in the Netherlands (Schoon and van Minnen, 1994); in particular 201 roundabouts were investigated. Specifically, a before-and-after comparison of intersections and roundabouts at 181 locations, based on the accidents occurred from 1984 to 1991 (including accidents with material damage only), showed that the number of accidents per intersection per year was reduced from 4.9 to 2.4 and the number of casualties was also reduced from 1.3 to 0.37 per year (in other words, there was a 47 percent reduction in the number of accidents and a 71 percent reduction in the number of fatalities).

The study also highlighted the following:
- the conversion from a four-arm controlled intersection to a four-arm roundabout is better in terms of safety when compared to the conversion from a three-arm controlled intersection to a three-arm roundabout, with regard to the bigger reduction in the total number of conflict points for four-arm roundabouts;
- the conversion from the old priority rule (give way to entering vehicles) to off-side priority (give way to circulating vehicles) determined a decrease of 75.1 percent in fatalities. By contrast, signalised intersections converted to roundabouts showed a reduction (2.7 percent) in accidents at nine sites and a slight increase (4 percent) in moped and cycle casualties.

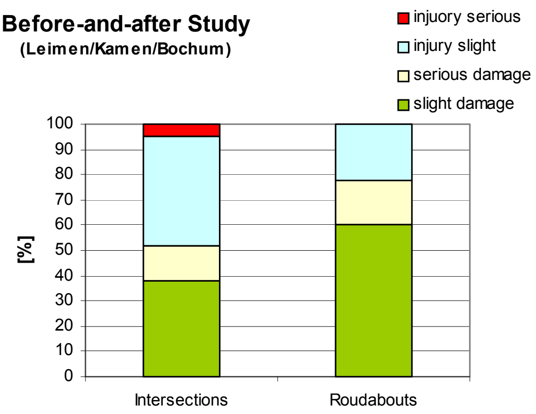


Figure 1: Absolute number of accidents per year (Stuwe, 1991)

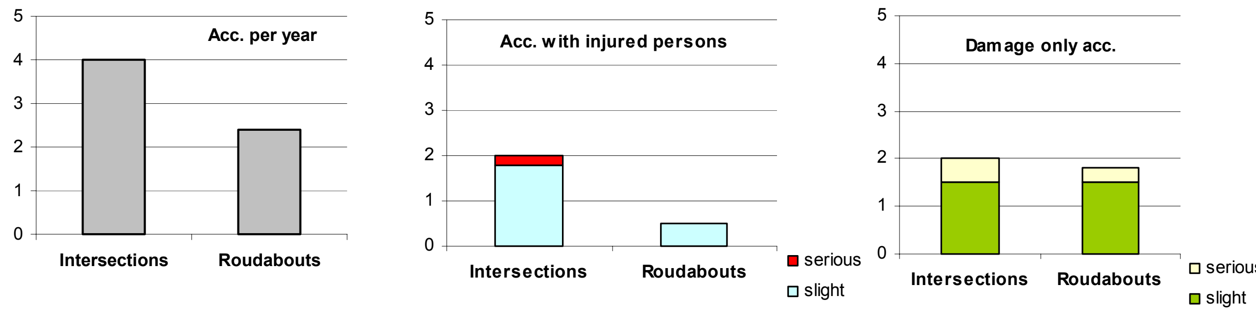


Figure 2: Accidents with injured persons or damage only (Stuwe, 1991)

With regard to specific engineering measures for cyclists and moped riders (possible presence – or absence – of a cycle lane on the roundabout or a separate cycle path for cyclists), the accident study carried out by Schoon and van Minnen (1994) highlighted the scanty effectiveness of the cycle lanes put beside the circulatory roadway of roundabouts (the percentage reduction in accidents is relatively the same at roundabouts without specific engineering measures for cyclists); by contrast, the presence of a separate cycle path for cyclists gave better performances in terms of safety for cyclists (90 percent reduction in accidents for roundabouts without a separate cycle path for cyclists).

A before-and-after study carried out in the greater London area (Lalani, 1975), based on the examination of 38 roundabouts of various diameters (twenty mini-roundabouts, nine small roundabouts, five large roundabouts and four double-mini roundabouts), showed the following:

- reductions in overall accidents (about 39 percent) and particularly: 30 percent for mini-roundabouts (1 to 4 metres in diameter), 43 percent for small roundabouts (4.1 to 7.9 metres in diameter), 52 percent for large roundabouts and 40 percent for double-mini roundabouts;
- reductions in pedestrian accidents and in vehicle accidents (about 40 percent and 39 percent respectively); for vehicle accidents, the fall could be attributed to accidents that were formerly cross-road and left-turner type (since nose-to-tail and single-vehicle accident rates remained fairly stable);
- fatal and serious vehicle accidents showed a decrease of 69 percent and accounted for a reduction in all accidents from 17 percent to 10 percent;
- 23 percent reduction in overall accidents at roundabouts with a curbless island; by contrast, nose-to-tail collisions rose by 60 percent and two-wheeled vehicle accidents rose by 7 percent.

An American before-and-after comparison of six sites that were converted from T and cross intersections (both stop-controlled and signalised) to roundabouts revealed favourable safety performance of roundabouts (Flannery and Datta, 1996), particularly in terms of reduction in accident frequency.

Similar results were obtained in Norway by a risk analysis carried out in 1990, based on the integrated examination of accident data from 1985 to 1989 at 59 roundabouts and 124 signalised intersections and traffic data surveyed during the same time (Seim, 1991). The risk was measured by accident rate (see Table 2) and defined as the number of personal injuries per million vehicles per year crossing the intersection.

The analysis of international accident studies, as above reported, allows to underline that reduction of crash rate and severity, characterizing roundabouts compared with traditional intersections, is attributable to the reduction of potential conflicts, in relation to the peculiar geometric configuration of roundabouts, as well as to the reduction of the absolute speeds of both vehicles or the angle between the vehicle paths (reducing the potential relative speed between two vehicles at the point of conflict); the limitation of the variation in speed

Table 2: Accident Rates

Number of Arms	Roundabouts	Traffic Signals
3	0,03 (0,05)*	0,05 (0,08)
4	0,05 (0,04)	0,10 (0,16)
* Number in parentheses is from earlier studies		

between consecutive horizontal geometric elements is another characteristic element of safety of roundabouts.
Moreover, knowledge relating to traffic safety at roundabouts is not an exhaustive reference for geometric design when there are organizational schemes for intersections characterized by physical constraints that render it necessary to make “compromise solutions” relating to one or more geometric features of the roundabout (“Roundabout Inspired Intersections” – RI intersections). The wide variety of geometric layouts that, together with the variety of local situations, characterizes this kind of roundabouts often causes the acceptance of road circular schemes characterized by traffic conditions very different from traditional roundabouts and makes very complex the evaluation of performances, in particular, as regards road safety.

ACCIDENT PHENOMENOLOGY ANALYSIS FOR THE RI INTERSECTIONS

Previous Research

The theme of atypical intersections and roundabout inspired intersections is, in particular, the object of previous researches; the experimental base of observations has been represented by roundabouts belonging to the road network in Palermo.
The examination of these intersections, because local constraints influenced their installations, showed organizational schemes for junctions characterized by a geometric design requiring quite different driving behaviours from those that are observable at roundabouts.
Moreover, in almost all case studies the conditions of anticipation and readability are poor; observing road user behaviour, site visits highlighted the recurrent riskiness of some road situations, attributable to local geometric defects and, in particular, to improper driver behaviour misled by the infrastructure.
A pilot sample of RI intersections was extracted from the whole sample of RI intersections, as above identified. An aggregate study of accidents (Granà, 2002), based on accident data from 1996 to 2000 was carried out for this pilot sample; the findings included evaluation of the frequencies of peculiar collision types and further specific aspects like crash location, types of accident-causing factors, crash percentage per type of user, the breakdown of accidents by time bands, etc.. Figure 3 shows some examples of the RI intersections examined.

Figure 3: Examples of RI intersections

A safety diagnostic method at RI intersections was applied by means of a delocalisation procedure, based on the identification of similar road situations (infrastructural scenarios) recurrent in the RI intersections of the pilot sample.
The disaggregation of accidents and their grouping by infrastructural scenario made it possible to evaluate the risk correlated to each infrastructural scenario; for this purpose, a relative risk model was gauged with reference to the strength of the observed crash phenomenon, considering both total accidents and specific accident classes (Granà, 2004). So it was possible to evaluate the relative hierarchy of risk levels characterizing the infrastructural scenarios at RI intersections and the road safety performance as a function of systemic characteristics of RI intersections.

Ongoing of the Research and Articulation of the Present Paper

In the present research, based on the abovementioned results, the sample of RI intersections was enlarged and, subsequently, an endeavour was made to identify the relations between specific crash rates and geometric characteristics for the particular intersections examined.
The result, as afterwards reported, are based on the examination of 1383 accident data (where about 2/3 – 848 - are personal injury accidents) from 1996 to 2000 at 34 urban RI intersections.
Specifically, for each RI intersection, the start point of the analysis was focused on two subjects:

- the collection of accident data from reports of police authorities, considering personal injury accidents and accidents with material damage; accidents occurred within 20 meters from intersections were collected to consider the influence of the circulating traffic on entering traffic travelling along the arms;
- traffic surveys, made by three repetition of four hours, suitably distributed during the day, in working day (Tuesday, Wednesday, Thursday).

Figure 4 shows the whole of the study. The object of the present research is identifiable with the third phase.

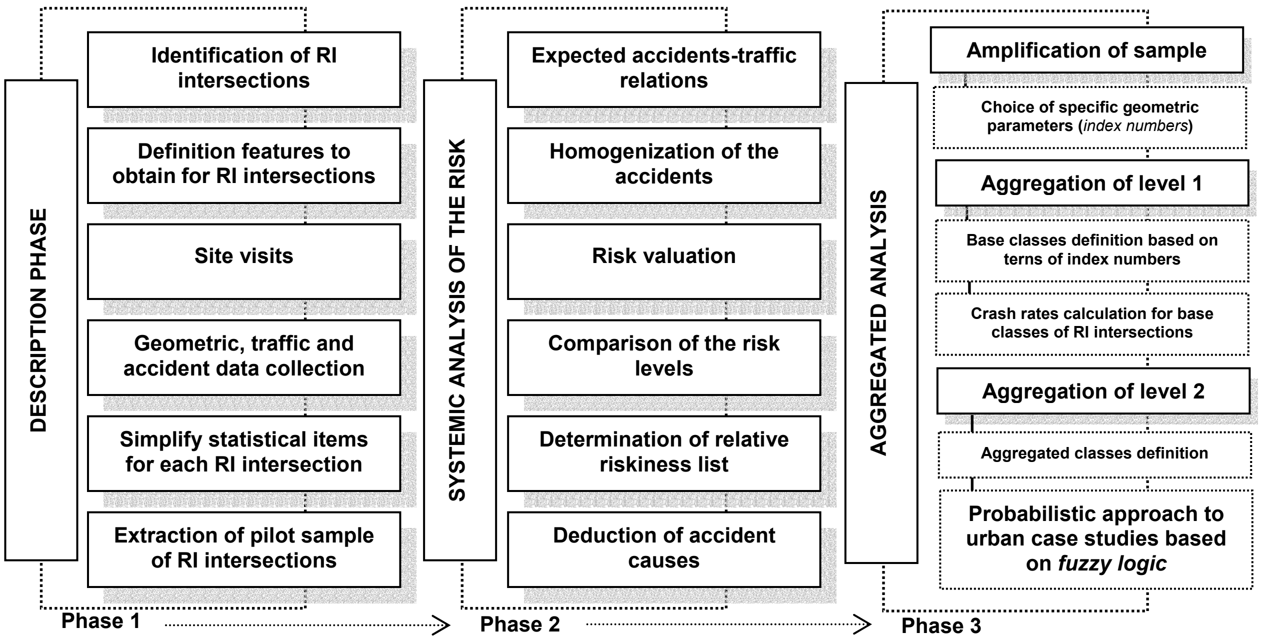


Figure 4: Phases and articulation of the research

Analysis Methodology for the Present Research

The aggregate accident analysis was completed by a probabilistic approach; specifically, for phase 3, fuzzy logic allowing strong aggregation of statistical information (Stewart, 1989; Berthold, 1999) was chosen.
It is common knowledge that fuzzy mathematics is more effective for processing insufficiently appreciable and uncertain data[3] than deterministic approaches.
For this reason, the probabilistic approach in fuzzy logic was applied in order to obtain immediately the distributions of crash rates for the RI intersection classes identified starting from the specific geometric characterization carried out for the purposes of this research.
The accident analysis developed in the present research was carried out according to two aggregation levels:

- one serving to define base classes of RI intersections, identified by terns of index numbers, structured starting from combinations of the values of three geometric parameters (central island radius, circulating width, number of arms). A tern of fuzzy numbers was associated with each class as identified above; the fuzzy numbers were obtained from accident numbers and severity (fatal and serious vehicle accidents) at RI intersections and from crash rates *I* and *It* (aggregation of level 1);
- one serving to define the aggregate classes of superior hierarchical level (aggregation of level 2) and to analyse the correlations between crash rates and different combinations of the geometric parameters examined.

FIRST LEVEL ANALYSIS

Geometric and Safety Characterizations of RI Intersections

Three ranges were identified for the geometric parameters mentioned above (i. R = central island radius [m]; ii. n = number of arms; iii. L = circulating width, identified by the number of circulating lanes); each range coincided with an index number (see Table 3).

The index number values varied from 1 to 3; based on numerous accident studies in the literature relating to the safety of traditional roundabouts, increasing values of the index number agree with increasing risk levels. Specifically:

- for the "central island radius" variable, the index number equal to three coincides with a situation characterized by less dynamic control of circulating and entering speeds and hence with an unfavourable outcome regarding accident frequency and severity;
- for the "number of arms" variable, the index number equal to three coincides with road situations characterized by a higher number of conflict points and hence by poorer performance in terms of safety;
- for the "circulating width" variable, the index number equal to three coincides with intersections characterized by a higher number of circulating lanes, along which it is possible to attain high speeds.

On the basis of the above, 3^3 = 27 base classes of RI intersections were examined; each class was characterized by a tern of index numbers, considered according to the order shown in Table 3. Then each class defined as above (aggregation of level 1) was characterized from the accident point of view.

Table 3: Index numbers

R	index number	n	index number	L	index number
R ≤ 20 m	R=1	n=3	n=1	L=2	L=1
20 m < R≤ 40 m	R=2	n=4	n=2	L=3	L=2
R> 40 m	R=3	n>5	n=3	L=4	L=3

For this characterization conventional crash rates were used, as follows:

- the average accident rate per 1 million vehicles entering the intersections:

$$I = \frac{Acc \times 10^{-6}}{AADF \times 365}$$

where:

- Acc = number of personal injuries reported to police and occurring during one year of the study period
- AADF = average annual daily entering flow (vpd);

- the global crash rate, that is the economic damage caused by accidents, deaths and casualties, defined as follows:

$$I_t = \frac{A \cdot n + F \cdot f + M \cdot m}{AADF \times 365}$$

where, for each year:

- A = number of accidents
- F = number of casualties
- M =number of deaths
- AADF = average annual daily entering flow (vpd).

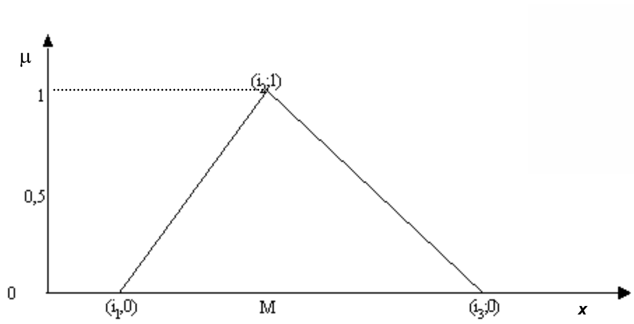
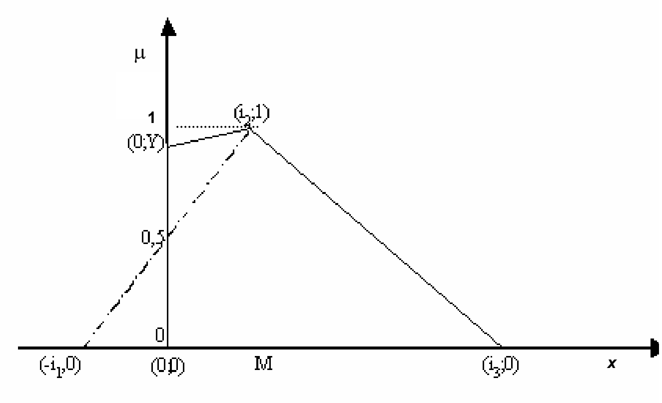
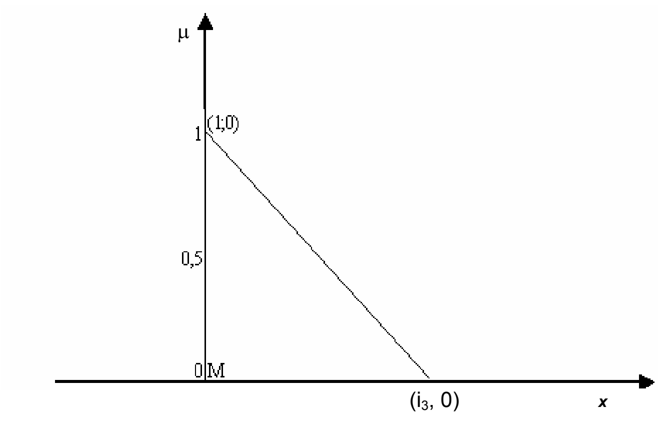
The equivalence coefficients n, f and m, calculated on the basis of disbursements by insurance companies, are respectively 1, 1,6 and 50.

Identifications of the Base Classes by Fuzzy Numbers

For each base class the crash rates (*I* and *It*), as defined above, have been determined over the duration of the study period (1996/2000); for the distributions, the mode and the absolute mean deviation (s^- and s^+) as to the mode were calculated.

From the calculated parameters of the distribution, a fuzzy number (FN) has been structured; it is the accident statistic distribution for each class. Table 4 shows the different possible cases; the same table shows the reduced fuzzy numbers (TFNr) that, as it is common knowledge, allow to simplify the subsequent aggregations and to work exclusively with triangular fuzzy numbers.

Table 4: Fuzzy Numbers

<table>
<tr><td>Fuzzy Numbers</td><td>CASES</td><td>FN</td><td>FNr</td></tr>
<tr><td colspan="4">Triangular Fuzzy Numbers</td></tr>
<tr><td rowspan="3">
</td><td rowspan="3">$M - 3s^- \geq 0$</td><td>$i_1 = M - 3s^-$</td><td>$j_1 = M - s^-$</td></tr>
<tr><td>$i_2 = M$</td><td>$j_2 = M$</td></tr>
<tr><td>$i_3 = M + 3s^+$</td><td>$j_3 = M + s^+$</td></tr>
<tr><td colspan="4">Fuzzy Number represented by a quadrilateral</td></tr>
<tr><td rowspan="4">
</td><td rowspan="4">$M - 3s^- < 0$</td><td>$i_1 = M - 3s^-$</td><td>$j_1 = M - s^-$</td></tr>
<tr><td>$i_2 = M$</td><td>$j_2 = M$</td></tr>
<tr><td>$i_3 = M + 3s^+$</td><td rowspan="2">$j_3 = M + s^+$</td></tr>
<tr><td>$Y = \frac{s^- - \frac{M}{3}}{\frac{2M}{3} - s^-}$</td></tr>
<tr><td colspan="4">Fuzzy Number represented by a right-angled triangle</td></tr>
<tr><td rowspan="3">
</td><td rowspan="3">$M = 0$</td><td>$i_1 = 0$</td><td>$j_1 = 0$</td></tr>
<tr><td>$i_2 = 0$</td><td>$j_2 = 0$</td></tr>
<tr><td>$i_3 = M + 3s^+$</td><td>$j_3 = M + s^+$</td></tr>
</table>

SECOND-LEVEL ANALYSIS

Once the reduced triangular fuzzy numbers (TFNr) have been determined, the second level of aggregation contemplates identification of the aggregate classes of the upper hierarchic level; the latter were obtained maintaining constant one value of the index number (R, n, L) and varying the other index numbers from one to three.

The reduced fuzzy numbers of the generic aggregate class $K_j = (k_{1j}; k_{2j}; k_{3j})$ are obtained using the following expression:

$$\left(\frac{\sum_{i_j} n_{i_j} j_{1,i_j}}{\sum_{i_j} n_{i_j}} ; \frac{\sum_{i_j} n_{i_j} j_{2,i_j}}{\sum_{i_j} n_{i_j}} ; \frac{\sum_{i_j} n_{i_j} j_{3,i_j}}{\sum_{i_j} n_{i_j}} \right) = \left(k_{1j}, k_{2j}, k_{3j}\right)$$

where the index i_j identifies the generic base class *i* belonging to the higher-order aggregate class *j*.
On the basis of the positions made, each element of the fuzzy number (k_{1j}, k_{2j}, k_{3j}) characterizing the aggregate class of higher order *j* is obtained as the average of the corresponding elements of the FNr characterizing the base class of index i_j, weighted with respect to the number of elements n_{ij} of each class.
On the basis of this information, it is possible to obtain the effective distribution of the accidents of the aggregate class of the higher hierarchic level. For the generic class *j* the following cases are possible:

a) $k_{2j} - 3(k_{2j} - k_{1j}) \geq 0$

in which case we will have a triangular fuzzy number, defined by the tern:

$$l_{1j} = (3k_{1j} - 2k_{2j})$$
$$l_{2j} = (k_{2j})$$
$$l_{3j} = (3k_{3j} - 2k_{2j})$$

b) $k_{2j} - 3(k_{2j} - k_{1j}) < 0$

in which case we will have a fuzzy number represented by a quadrilateral with the coordinates of the vertices equal {(0,0), (0, $\overline{Y}$), (l_{2j}, 1), (l_{3j}, 0)}; l_{2j} and l_{3j} are obtained from the relations given above and the intercept on the vertical axis is given by:

$$\overline{Y} = \frac{k_{2j} - k_{1j} - \frac{k_{2j}}{3}}{\frac{2k_{2j}}{3} - k_{2j} + k_{1j}} = \frac{\frac{2k_{2j}}{3} - k_{1j}}{k_{1j} - \frac{k_{2j}}{3}}$$

With the positions made, variations in accident frequency with variation in each geometrical parameter, while one index number remained unchanged and varying the other index numbers from one to three, were explored. Appendix A, by way of example, includes an extract from the worksheet relating to the aggregation operations carried out for the second-level analysis.

EVALUATION OF ACCIDENTS AT ROUNDABOUTS. APPLICATION TO CASE STUDIES IN THE URBAN ENVIRONMENT

In order to study correlations between accident rates (*I* and *It*) and the geometrical parameters of the intersection, for each aggregate class of intersections, characterized by a tern FNr, the explanatory parameters chosen (R, n, L) were varied one by one.
Among all possible correlations, some of the most significant are given by way of example. They are generated:

1. by variations in parameter L (circulatory roadway width) for R=1 (R ≤ 20 m) and n = 1, 2, 3 (Classes [R=1, n =1,2,3, L=var], see Figure 5);
2. by variations in parameter R (average central island radius) for n = 2 (four arms) and L = 1,2,3 (Classes [R=var, n =2, L =1,2,3], see Figure 6);
3. by variations in parameter L (circulatory roadway width) for n = 2 (four arms) and R =1,2,3 (Classes [R = 1,2,3, n =2, L=var], see Figure 7).

Classes [R =1, n =1,2,3, L=var]

The accident probability expressed by accident risk *I* shows a maximum for L=2 (three circular lanes); for a relatively high width of the circular lanes (L=3), the correlation in Figure 5 indicates a marked decrease in risk.
In a parallel way, for the same cases examined, the graph in Figure 5 also shows a decreasing accident pattern expressed by global crash rate *It*. The apparent contradictoriness of the pattern of the two correlations found can be resolved by hypothesising that an increase in the circulatory width producing two distinct but contrasting effects on accidents and their seriousness:

i) an increase in the potential conflict points between the flows into the ring and, consequently, a higher likelihood of collision, partly or wholly made up by the greater freedom of choice for users regarding their trajectory and position on the ring and, in the case of effective danger of an accident, greater easiness in making diversions and/or recovery manoeuvres;
ii) gradual diminution of the kinetic energy brought into play by the accident event due to the decrease in the collision angles, since fewer constraints are exerted by the geometry on the trajectory of circulating or entering vehicles and/or, as above, greater ease in managing the trajectory in the case of an emergency.

Classes [R=var, n =2, L =1,2,3]

In this case the accident risk *I*, in the conditions specified, shows progressive worsening of the risk conditions with an increase in the radius of the central island, and the further it moves into the field of big-diameter roundabouts the more marked it is.

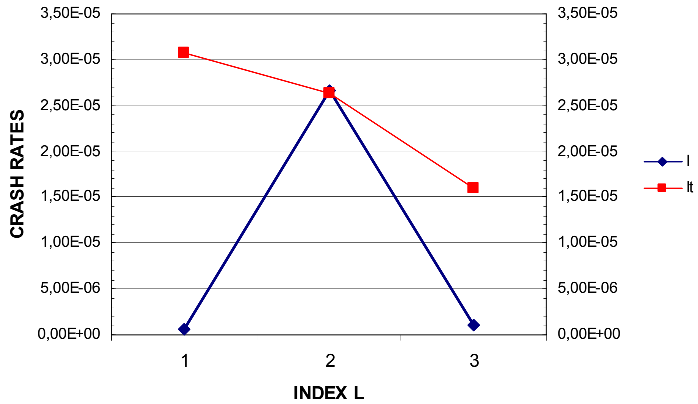
Global crash rate *It* shows a net minimum for radii between 20 and 40 metres; outside this interval, however, we observe comparable relatively elevated risk conditions, to be related to modifications made in the accident phenomenon, on account of altered working conditions of the intersection (see Figure 6). These changes concern:

- the distribution and the frequency of the different types of accidents (for example, with an increase in the radius the number and seriousness of accidents due to loss of control on entering increases);
- the severity of collisions (for high radii the higher speeds reached on the ring increase the seriousness of crashes between circulating vehicles as well as between circulating and entering vehicles, while the severity of accidents due to loss of control decreases).

Classes [R =1,2,3, n =2, L=var]

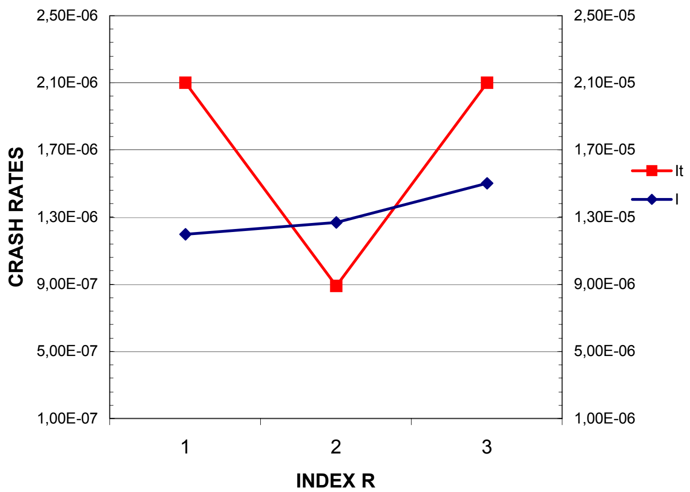
A further correlation examined concerned variations in the ring length L for RI intersections having four arms (see Figure 7). It was found that:

- the pattern of indicator *I* confirms what can be deduced from on-site observations (both during the present study and as reported in the literature); in other words that, though the main potential conflict points remain the same, the risk of accidents tends to increase with an increase in the circulatory roadway width;
- the probability of accidents with injuries *It* decreases with an increase in the number of circulatory roadways, i.e. though there are more accidents their consequences are less serious. This observation can be related to the altered collision dynamics already highlighted in the first of the cases examined.



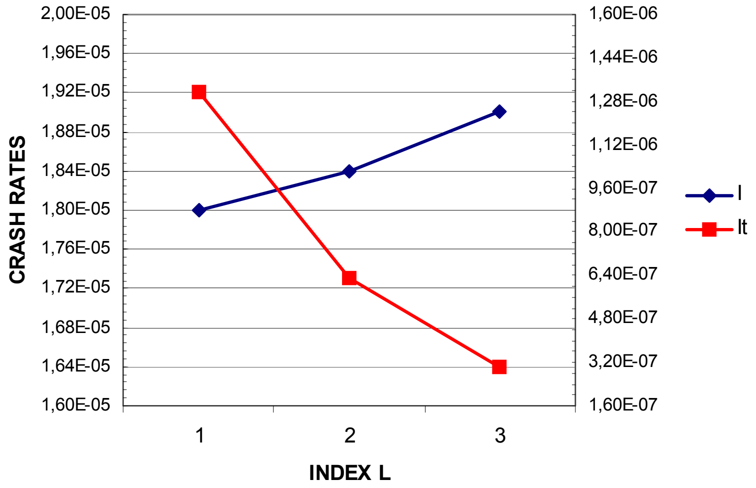
L	It	I
1	$3{,}10 \cdot 10^{-05}$	$6{,}5 \cdot 10^{-07}$
2	$2{,}60 \cdot 10^{-05}$	$2{,}66 \cdot 10^{-05}$
3	$1{,}60 \cdot 10^{-05}$	$1{,}1 \cdot 10^{-06}$

Figure 5: Correlation between crash rates and index L (circulating width expressed in terms of number of circulating lanes).



R	It	I
1	$2{,}1 \cdot 10^{-05}$	$1{,}2 \cdot 10^{-06}$
2	$8{,}9 \cdot 10^{-06}$	$1{,}3 \cdot 10^{-06}$
3	$2{,}1 \cdot 10^{-05}$	$1{,}5 \cdot 10^{-06}$

Figure 6: Correlations between crash rates and index R (central island radius).



R	It	I
1	$1,92\cdot10^{-05}$	$8,78\cdot10^{-07}$
2	$1,73\cdot10^{-05}$	$1,02\cdot10^{-06}$
3	$1,64\cdot10^{-05}$	$1,24\cdot10^{-06}$

Figure 7: Correlations between crash rates and index L (circulating width expressed in terms of number of circulating lanes).

CONCLUSIONS AND POSSIBLE DEVELOPMENTS

From the methodological viewpoint, the present study, in agreement with observations by various authors (Juang C.H. et al., 1993; Mauro R. et al., 1997; Kaufmann et al., 1988; Gatti et al., 2000), gives further confirmation of the possibility of using fuzzy logic for interpreting accident phenomena and for generalising the results of accident studies.
The exploratory investigation of a sample of RI intersections shows further characteristics of the analysis method that are worth stressing:

- the sensitivity of the model to variations in the explicative variables describing the geometrical and functional organisation of the intersection;
- the possibility of studying a relative risk level between different infrastructural arrangements, starting from the combination of the geometrical and functional parameters of the intersection;
- the possibility of interpreting the accident phenomenon even when the use conditions (particularly regarding traffic served and speed) and the structure of the phenomenon (accident typology, collision dynamics, etc.) are markedly different because of variations in the geometrical configuration of the intersection.

These further characteristics of the method, since they make it possible to evaluate the effects of the single composition variables and the combinations of the latter on safety, prove particularly useful in the development of instruments supporting both preventive safety analysis and the choices made by the designer called on to operate in the planning of new installations or re-qualification/reconversion of existing installations.

ENDNOTES

[1] In Italy, the traffic control for roundabouts is ambiguous; the highway code says at the 145 section that drivers has to give way to traffic coming from the right, except for different signal, but doesn't say anything about the opportunity (or the duty) to extend to the existing roundabouts the conversion from the old priority rule (give way to entering vehicles) to off-side priority (give way to circulating vehicles).

[2] Recent studies (Brown, 1995) highlighted that small roundabouts can be installed to take the place of traditional intersections characterized by high accident rates, also if the benefits aren't so pronounced as in conventional roundabouts.

[3] The characteristic values in fuzzy logic are fuzzy numbers; they allow one to aggregate and disaggregate available data in a simple way and with a satisfactory level of approximation compared to probabilistic distributions.

REFERENCES

Berthold M. B., (1999). *Fuzzy Logic*. In *Intelligent Data Analysis*, pp 168-298, Ed. by Sprinter, Berkeley , USA.

Brown M., (1995) *The design of roundabout, State of the art review, Transportation Research laboratory –* Department of Transport, London U.K.

Flannery A. and Datta K. (1996). *Modern Roundabouts and Traffic Crash Experience in United States. Transportation Research Record 1553*. pp. 103-109, Washington, USA.

Gatti G., Cavuoti E. (2000). *La classificazione delle strade ai fini della sicurezza. La sicurezza stradale Vol. 4, Coll. di Ingegneria delle Infrastrutture Viarie*, pp. 75-112, Ed. by Aracne, Forlì, Italy.

Granà A. (2002). *Criteri di sicurezza per la valutazione preventiva del rischio di sistemazioni atipiche. L'analisi per scenari infrastrutturali*, pp. 430-439, Ed. by la Fiaccola srl, Milan, Italy. In Atti del XXIV Convegno AIPCR. Saint Vincent (Aosta).

Granà A. (2004). *Safety diagnostic method in urban circular intersections.* In *The International Conference "The Urban Transport 2004" Proceedings. Dresden (Germany), May 2004.*

Lalani, N. (1975). *The Impact on Accidents of the Introduction of Mini, Small and Large Roundabouts at Major/Minor Priority Junctions. Traffic Engineering & Control*, pp. 560-561, London, U.K.

Juang, C. H. et al., (1993) *Representation processing and interpretation of fuzzy information in civil engineering.* TTR 1399.

Kaufmann A., et. Al., (1988). *Fuzzy mathematical models in Engineering and management science.* North Holland.

Mauro R. et al., (1999) *Un metodo per l'analisi della pericolosità delle intersezioni non semaforizzate basato su logiche fuzzy*, pp. 483-502. Ed. by Franco Angeli, Milano, Italy.

Maycock, G. and Hall. R. (1984). *Accidents at 4-arm roundabout. Transport and Road Research Laboratory* (TRRL Laboratory) Report LR 1120. - Southampton University - England.

Ourston L. and Doctors P. (1995). *Roundabout Design Guidelines. Ourston & Doctors Modern Roundabout Interchanges,* London, UK.

Stewart I. (1989). *Does God play dice? The mathematics of chaos*. Ed. By Blackwell, Cambridge MA.

Schoon, C., and J. van Minnen (1994). *The Safety of Roundabouts in The Netherlands. Traffic Engineering and Control*, pp. 142-148, Vol. 35, No. 3, Netherlands.

Seim K. (1991). *Use, Design and Safety of Small Roundabouts in Norway. Intersection without Traffic Signals II*, pp. 270-281, Ed. by Springer-Verlag, Werner Brilon, Germany.

Stuwe B. (1991), *Capacity and Safety of Roundabouts-German Results. Intersection without Traffic Signals II,* pp. 1-12. Ed. by Springer-Verlag, Werner Brilon, Bochum (Germany).

Tudge, R.T. (1990). *Accidents at Roundabouts in New South Wales*. Proceedings 15th ARRB Conference, Vol. 15, Part 5, New South Wales, Australia.

APPENDICES

An extract from the worksheet is shown below. Specifically Table 5 refers to the characterisation of the base classes regarding accidents and the calculation of the reduced fuzzy numbers (1^{st} aggregation level), while Table 6 shows the calculation of fuzzy numbers for the aggregate classes (2^{nd} aggregation level).

Table 5

elements of classes	2		3		2		2		2	
classes	1	111	2	121	3	131	4	112	5	122
	It	I	It	I	It	I	It	I	It	I
CRASH RATES (YEARS 1996-2000)	3,811E-07	3,462E-07	1,47E-07	5,74E-07	7,27E-07	4,90E-07	2,84E-07	2,84E-07	2,03E-06	1,32E-06
	7,55E-07	3,655E-07	2,82E-07	1,41E-07	9,056E-07	7,27E-07	2,91E-07	2,91E-07	2,30E-06	8,53E-07
	1,29E-06	3,81E-07	3,15E-06	1,47E-07	5,41E-07	7,46E-07	3,11E-07	3,11E-07	6,56E-06	1,02E-06
	1,327E-06	6,99E-07	3,06E-06	1,14E-06	2,17E-06	9,55E-07	3,19E-07	3,19E-07	9,24E-06	1,14E-06
	2,378E-06	7,17E-07	3,58E-06	1,17E-06	9,87E-07	1,18E-06	3,23E-07	3,23E-07	9,31E-06	1,13E-06
	2,747E-06	7,55E-07	9,14E-07	2,82E-07	1,25E-06	2,01E-07	3,27E-07	3,27E-07	9,337E-06	1,21E-06
	1,41955E-05	7,74E-07	1,06E-06	2,86E-07	1,11E-05	3,47E-07	5,59E-07	5,59E-07	1,28E-05	1,24E-06
	1,50E-05	1,07E-06	1,029E-06	2,90E-07	1,22E-05	3,53E-07	5,73E-07	5,73E-07	1,29E-05	1,27E-06
	1,65E-05	1,11E-06	1,016E-06	1,68E-06	7,89E-07	3,86E-07	6,29E-07	6,29E-07	1,61E-05	1,29E-06
	1,81E-05	1,47E-06	1,03E-06	4,29E-07	1,28E-06	3,62E-07	8,30E-07	8,30E-07	1,79E-05	1,17E-06
			5,04E-06	2,98E-07						
			1,07E-06	2,22E-06						
			1,33E-06	5,59E-07						
			2,65E-05	5,79E-07						
			5,799E-06	5,86E-07						
Statistical parameters										
maximum value	1,81E-05	1,47E-06	2,65E-05	1,68E-06	1,22E-05	1,18E-06	2,84E-07	8,30E-07	1,79E-05	1,32E-06
minimum value	3,81E-07	3,46E-07	1,4691E-07	1,47E-07	9,06E-07	3,19E-07	2,91E-07	2,84E-07	2,03E-06	8,53E-07
mean	7,26E-06	7,69E-07	3,67E-06	6,91E-07	3,20E-06	5,75E-07	4,45E-07	4,45E-07	9,86E-06	1,16E-06
median	2,56E-06	7,36E-07	1,07E-06	5,59E-07	1,12E-06	4,38E-07	3,25E-07	3,25E-07	9,32E-06	1,19E-06
m.s.d.	2,26E-05	1,10E-06	5,01E-06	2,26E-06	1,34884E-05	9,45E-07	2,10E-05	5,69E-07	1,59209E-05	3,04419E-05
mode	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
s-	5,78E-06	1,92E-07	1,70E-06	2,11E-07	2,12E-06	1,14E-07	5,84E-08	7,12E-08	3,40E-06	1,02E-07
s+	8,67E-06	5,00E-08	1,25E-06	2,95E-07	8,47E-06	2,66E-07	5,00E-09	2,85E-07	5,00E-07	1,02E-07
Fn										
j1	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
j2	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
j3	8,67E-06	5,00E-08	1,25E-05	2,95E-07	8,47E-06	2,66E-07	5,00E-09	2,85E-07	5,00E-07	1,02E-07
Y	-	-	-	-	-	-	-	-	-	-
i1	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
i2	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
i3	2,60E-05	1,50E-07	3,74E-05	8,84E-07	2,54E-05	7,98E-07	1,50E-08	8,54E-07	1,50E-06	3,065E-07

Table 6

A) CLASSES [R =1 n = var, L=1]							
INDEX NUMBER	ELEMENTS	It			I		
		j_1	j_2	j_3	j_1	j_2	j_3
111	2	0	0	$8{,}67\cdot10^{-6}$	0	0	$5{,}00\cdot10^{-8}$
121	3	0	0	$1{,}25\cdot10^{-5}$	0	0	$2{,}95\cdot10^{-7}$
131	2	0	0	$8{,}47\cdot10^{-6}$	0	0	$2{,}66\cdot10^{-7}$
	TOT. 7	K_1	K_2	K_3	K_1	K_2	K_3
		0	0	$1{,}02\cdot10^{-5}$	0	0	$2{,}17\cdot10^{-7}$
		I_1	I_2	I_3	I_1	I_2	I_3
FN of the aggregated classes		0	0	$3{,}07\cdot10^{-5}$	0	0	$6{,}50\cdot10^{-7}$

B) CLASSESI [R =1 n = var, L=2]							
INDEX NUMBER	ELEMENTS	It			I		
		j_1	j_2	j_3	j_1	j_2	j_3
112	2	0	0	$5{,}00\cdot10^{-9}$	0	0	$2{,}85\cdot10^{-7}$
122	2	0	0	$5{,}00\cdot10^{-7}$	0	0	$2{,}58\cdot10^{-5}$
132	2	0	0	$2{,}58\cdot10^{-5}$	0	0	$5{,}61\cdot10^{-7}$
	TOT. 6	K_1	K_2	K_3	K_1	K_2	K_3
		0	0	$8{,}76\cdot10^{-6}$	0	0	$8{,}88\cdot10^{-6}$
		I_1	I_2	I_3	I_1	I_2	I_3
FN of the aggregated classes		0	0	$2{,}63\cdot10^{-5}$	0	0	$2{,}66\cdot10^{-5}$

follows table 6

c) CLASSES [R =1 n = var, L=3]							
INDEX NUMBER	ELEMENTS	It			I		
		j_1	j_2	j_3	j_1	j_2	j_3
113	2	0	0	$6{,}07 \cdot 10^{-6}$	0	0	$5{,}55 \cdot 10^{-8}$
123	2	0	0	$5{,}09 \cdot 10^{-6}$	0	0	$8{,}53 \cdot 10^{-7}$
133	2	0	0	$4{,}84 \cdot 10^{-6}$	0	0	$1{,}72 \cdot 10^{-7}$
	TOT. 6	K_1	K_2	K_3	K_1	K_2	K_3
		0	0	$5{,}33 \cdot 10^{-6}$	0	0	$3{,}60 \cdot 10^{-7}$
		I_1	I_2	I_3	I_1	I_2	I_3
FN of the aggregated classes		0	0	$1{,}60 \cdot 10^{-5}$	0	0	$1{,}08 \cdot 10^{-6}$