Roundabout’s Performance Evaluation

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Synopsis

The paper deals with traffic management and in particular with the estimation of roundabout’s performances.
Many approaches have faced the problem of entry capacity and delays estimation; anyway, there is not a common and universally accepted procedure to the evaluation of roundabouts. Many models refer to an empirical approach; many others refer to a more theoretical one. Furthermore, all these approaches consider the roundabout facility as a succession of independent intersections, whilst, mainly in congested facilities, it should be considered as a multi-junction node.
In this paper, a new approach is presented, refined and applied: the input legs and the circulatory area of a roundabout facility are modeled as elements of a multi-junction node.
The new approach allows the estimation of capacity and delays for each entry leg and for the node as a whole. It is based on a model developed for on-ramp junctions segments on freeways; the same model has been applied to each approach leg of a roundabout, and specific requirements due to the presence of a circulatory roadway have been met. In this context the main problem is the relationship between the circulating and the entry flows in each input leg: this problem could be solved through an iterative process in order to find a final equilibrium solution.
If the circular relationship between entering and circulating vehicles has been solved, it is possible to well estimate entry capacity and queues development for each approach leg within a given time interval step; in such a way, it is possible to overcome the hypothesis of the roundabout as a succession of independent T-intersections.
Queues evolutions could be studied in a more detailed way than in a macroscopic approach. At the same time, the proposed method could be classified as a mesoscopic one, because it doesn’t need the amount of parameters and hypotheses which are needed for a microscopic method.
First results of the proposed model have been deeply compared to the results of existing macroscopic and microscopic models; the proposed procedure is in accordance with existing models throughout a correct calibration of the parameters introduced.

Roundabout’s Performance Evaluation

The paper deals with the problem of un-signalized roundabout’s performances evaluation, mainly focusing on Capacity and Level of Service (LOS) attributes. The paper refers to modern roundabouts, which usually operate under the off-side priority rule; in this case, the entry capacity for each approach leg depends mainly on the circulating flow around the roundabout.

Many different capacity models have been developed in the scientific literature, but they do not lead to homogeneous results, mainly under peak traffic conditions. These models usually analyze a roundabout as a simple succession of some stop or yield controlled independent intersections. The main problem of this procedure is that the traditional methods for the analysis of yield intersections could not be easily applied in modern roundabouts because of the nearness between the entry legs. Only in some particular cases, a roundabout could be studied as a simple succession of independent T-intersections: in such cases, traffic volumes are so low that the approach legs of the roundabout could be considered as totally independent.

For all these reasons, roundabouts have been studied traditionally as a specific kind of intersection; two main approaches have been developed for the Capacity and Level of Service evaluation: a macroscopic approach and a microscopic one. These approaches are very different from both a methodological and an operational point of view; at the time, neither the macroscopic approach nor the microscopic one have never completely guaranteed a satisfying level of agreement with data recorded from the field. Different models give different results, both under light and congested traffic conditions. So, a universal methodology that could well perform under different traffic or environmental conditions seems not to be really available.

In this context, the paper firstly reports a detailed classification of these two main approaches, showing and comparing their main differences.

Then, an original approach for roundabout’s performances analysis is presented. The main idea of this approach is that a roundabout could be studied as a succession of merging, weaving and diverging areas instead of a simple succession of some stop or yield controlled independent intersections. Of course, some of these operations could be neglected, depending mainly on the facility size and on interactions between vehicles. In most cases, mainly in modern roundabouts, the entry capacity estimation depends heavily on merging areas: actually, the capacity of each entry leg (and of the facility as a whole) depends on the relationship between the entering vehicles and the circulating ones.

The most important targets of this paper are the followings:

- to go in detail on a roundabout’s performances evaluation;
- to develop an original general framework for roundabout’s Capacity and LOS estimation;
- too propose a methodological procedure that could be set between a macroscopic and a microscopic approach and that could include (on the basis of a data based parameters calibration) both the two main existing approaches;
- to apply a mesoscopic model for merging areas that could be able to analyze vehicle interactions and quantify entry capacity and queues dynamics.

The paper is organized as follows: the next section briefly describes the major basic sets for the roundabouts performances evaluation and reports also a brief review on the Statistic and Probabilistic approaches. Then, the third section presents some main notes on the performance analysis on roundabouts. The fourth section introduces the main features of the proposed approach. Some applications to a case study are illustrated and main results are discussed in the fifth section. Finally some conclusions are drawn.

BACKGROUND

There are many classifications for roundabouts. The efficiency of a roundabout depends on some main elements that have to be taken into account at the beginning of the design procedure; these main elements are the followings:

- the daily traffic approaching to the node;
- the inscribed diameter of the facility;
- the project speed on the circulatory roadway;
- the project vehicle;
- left turning percentages.

In terms of these parameters, roundabouts could be classified in the following way:

- mini-roundabouts;
- compact roundabouts;
- urban roundabouts and rural roundabouts, with 1 or 2 lanes in the circulatory roadway.

Such a classification and similar ones are very useful to help the designer when the main geometric parameters have to be assigned to the facility.

Then, a more detailed analysis has to focus on peak hours and on each single approach separately; vehicles distributions and vehicles volumes have to be carefully studied in order to guarantee at least a sufficient Level of Service of the facility.

Roundabout’s performances are measured by the entry capacity, by delays and by queues lengths on each entry leg; in addition, the efficiency of the node as a whole could be measured by the mean delay and by the capacity of the node.

In modern roundabouts, the entry capacity for each approach leg depends on the circulating flow. The two main approaches to study roundabout’s performances differ for the particular relationship between the entry flow and the circulating one: the entry capacity could be managed at a macroscopic level or at a microscopic one. Main differences between these two approaches are here briefly recalled.

Statistical approach

The statistical approach analyses the interactions between the entry and the circulating streams (sometimes also the diverging streams) by a regression analysis on a wide data recorded set. The entry-circulating relationship depends on the geometrical parameters of the facility (circulatory roadway, entry and diverging legs). The geometric parameters are the most important factors in order to correctly evaluate the entry capacity and to improve the Level of Service of the facility.
Many different methods have been developed in this way and different geometric parameters have been introduced within each method. The entry capacity is usually a linear function of the circulating flow (in one case also of the diverging flow); the relationship depends only on the geometry of the approach legs and of the circulatory roadway.
The regression analysis requires a great amount of data on congested approach legs and on roundabouts of different size in order to generalize the entry capacity expression. This is actually the main fall of the statistical approach, because the capacity formulation (and also the delays formulation) could not be easily generalized; on the other side, the macroscopic approach allows a direct correlation between the geometric parameters of the facility and its performances.
The general entry capacity formulation for each approach leg is the following one.
Let
ONRO be the entry capacity for the minor stream (vph),
MI be the circulating flow (vph),
MI_d be the diverging flow (vph),
the entry capacity relationship follows:
ONRO = $f(MI, MI_d, Geometry)$, *vph.*

As an example, the entry capacity model developed in Germany is reported below.
ONRO = $C+D*MI$ (vph);
where *C* and *D* are constants reported in the following table.

Tab 1: Coefficients in the German macroscopic model

N° Entry/Circulating lanes	C	D
1/1	1218	-0,74
1/2 or 1/3	1250	-0,53
2/2	1380	-0,5
2/3	1409	-0,42

In the following picture the entry-circulating relationship is described in the case of one entry lane and one circulating lane roundabout.

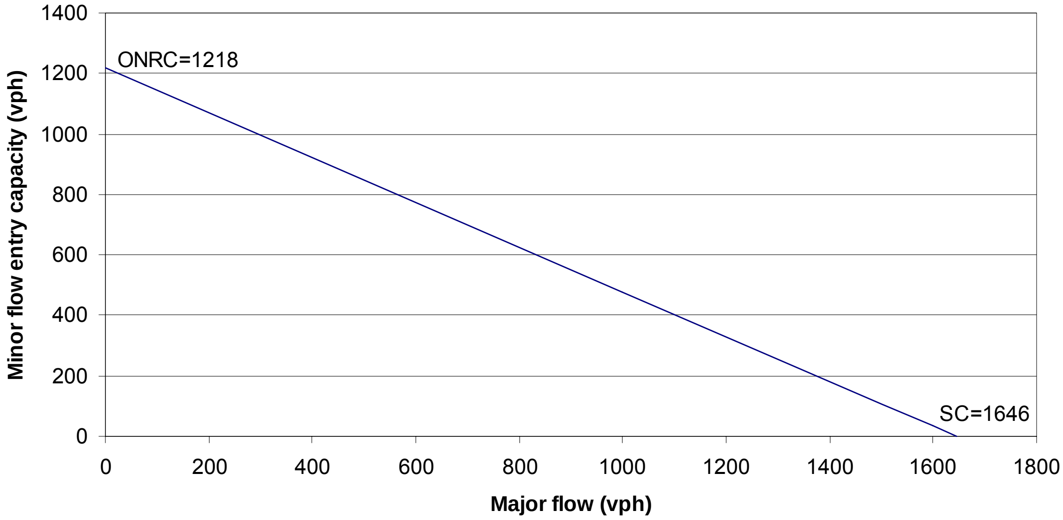

Figure 1: German linear model

As reported in the figure, SC represents the mainline capacity (no inflow entering from the approach leg); on the other hand, ONRC represents the entry capacity highest limitation (when there is a permanent queue on the approach leg whilst the major flow is null). Entry capacity could not overcome this limitation (that depends only on the geometry of the merge area). Usually entry capacity is reduced by the circulating flow: in particular, when the major flow reaches its maximum value (SC), entry capacity is reduced to zero.

Many geometric parameters have been introduced in the models developed within a macroscopic approach.
The model developed in England by Kimber needs the geometric details of the approach leg and of the merge area. Other models need, for example, only the widths of the circulatory roadway and of each approach leg.
Entry capacity depends directly on the circulating flow; in France and in Switzerland, entry capacity is influenced also by the diverging flow.
All these models have been developed by regression analysis on congested legs, and so entry capacity values are related to critical conditions. As a consequence, it is hardly recommended not to overcome the saturation index value of 0,85 in each approach leg: if this condition is satisfied, it is conventionally assumed that each approach leg could avoid saturation phenomena.

Probabilistic approach

Probabilistic methods refer to the interaction between single vehicles, following the Gap-Acceptance theory. They are more structured from a theoretical point of view; also a lane-by-lane analysis could be managed.
On the other hand, the probabilistic approach needs the calibration of the headway's distribution formulation (for both the major flow on the circulatory roadway and for the minor flow on the approach leg) and it needs also the calibration of some microscopic parameters (critical gap, minimum headway and follow-up time).
The calibration procedure is a very troublesome task, mainly for the extremely variable traffic flow conditions a roundabout should manage. Usually microscopic parameters are not measured on the field; they are given by some constant values that are then lightly adjusted by the geometry and the traffic features of the node.
In some models, the entry capacity evaluation depends also on the number of entry and circulating lanes (i.e. the Australian one developed by Troutbeck).
The relationship between the entry and the circulating flow is an exponential one.
As an example of the probabilistic approach, the entry capacity model developed in Germany (following the Gap-Acceptance theory) is reported below.
Let
ONRO be the entry capacity for the minor stream (vps),
MI be the circulating flow (vps),
T, T_o, Δ, t_o be microscopic parameters (s),
n_c, n_e be the circulating and entry lanes number,
following equation and parameters values hold:

$$ONRO = ((1-\Delta \cdot \frac{MI}{n_c})^{n_c}) \cdot (\frac{n_e}{T_0}) \cdot e^{-MI\cdot(t_0-\Delta)} \text{ (vps)}$$

Tab 2: Coefficients in the German microscopic model

Microscopic parameters (s)	Values
Critical Gap (T)	4.12
Follow-up time (T_o)	2.88
Mainline minimum headway (Δ)	2.10
t_o=T-T_o/2	2.68

The following picture reports the entry-circulating relationship in the case of one entry lane and one circulating lane roundabout. The parameters have been calibrated in Germany.

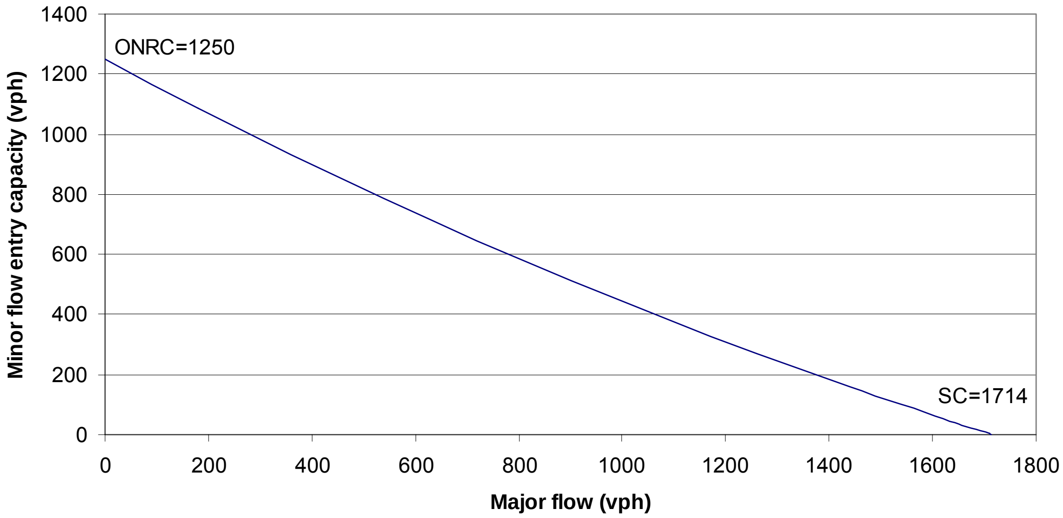

Figure 2: German exponential model

Very few geometric parameters are introduced in probabilistic models; they are usually the width of each approach leg and the width of the circulatory roadway (expressed in meters or expressed in the number of lanes). These two references to the geometry of the merge area allows to modify the values of the microscopic parameters and then to assign the entry and the circulating flows to the lanes.
Vehicles distribution on the major flow could be uniform or completely random; in addition, vehicles could be partially grouped in platoons. The best headway distribution function of the major flow has been tested to be the M3 distribution (the so-called Cowan distribution); it is based on the following hypothesis:

- vehicles random arrivals follow an exponential distribution;
- a percentage of arriving vehicles are grouped in platoon (θ);
- vehicles in platoons are uniformly separated by the headway Δ (s).

As an example, the entry capacity formulation developed by Troutbeck in Australia follows:
$ONRO = (1-\theta)*MI*exp(-\lambda*(T-\Delta))/(1-exp(-\lambda*T_o)$,
where λ is a decay parameter (it depends on the microscopic ones).

PERFORMANCE ANALYSIS

Capacity and Level of Service evaluation depend on the traffic conditions the facility has to face with. Usually roundabout's performances are evaluated using three basic measures:

- capacity estimation when all approach legs are congested;
- capacity estimation far away from the saturation in each approach leg;
- the Level of Service (LOS), expressed by delays and queue lengths.

Congestion on all approach legs

The first basic measure represents the ability of the roundabout to process traffic under heavy traffic conditions, when all approach legs have queues; capacity on congested conditions is given by the summation of the entry lane capacity over all approach lanes of each leg. Geometrical and behavioral considerations aside, this measure depends mainly on the Origin/Destination flows pattern. Under congested conditions, the entry capacity could be defined for each approach leg and for the facility as a whole, introducing the concepts of simple capacity and total capacity:

- Simple capacity, that is the entry capacity of an approach leg when a continuous queue is present on the entry lane;

- Total capacity, that is the capacity of the entire node, given by the addition of all simple capacities.

In this case, the facility could not be rightly considered as a succession of independent T-intersections: the entry capacity strictly depends on vehicles entering from the other legs. In particular, if a queue is present in a given entry leg, the entry capacity (that is a simple capacity) has not to be considered as a fixed value, because it decreases if the circulating flow increases. As a consequence, the entry capacity does not depend only on the geometric features of the merge area neither on the traffic flows involved on that particular merge area: it depends on all demand flows and it has to be evaluated in an iterative way.

When the less critical approach reaches its simple capacity, the simple capacity of the other legs reaches its minimum value. In these conditions, the roundabout could not self-regulate well and delays increase very rapidly.

Some existing models allow to measure delays and queue lengths for each approach leg; many of them could not be directly applied in the case of an over saturation condition and so a more complex model has to be applied.

In addition, some others effects due to the congestion conditions could begin and become significant: these phenomena are for example the “Limited priority merge” and the reduction of the “Critical Gap” value due to high waiting times. These effects could not be easily modeled in a general entry capacity formulation that should cover both the under-saturation and the over-saturation conditions.

In the over-saturation case, the roundabout has to be studied as a multi-junction node; in this case, the signalization of the facility could be a possible solution to reduce the negative effects of congestion.

Congestion on some approach legs

In a more general situation, some approach legs may be not saturated; in this case, the flow approaching the facility (that is the demand flow) is lower than the entry capacity and is defined as “the maximum rate at which vehicles can reasonably be expected to enter the roundabout from an approach during a given time period under prevailing traffic and geometric conditions”. As a consequence, vehicles demand and entry flow assume the same value. The maximum flow that could enter into the roundabout under no congested conditions is the second basic measure of performances for a roundabout.

In stable conditions, roundabouts could be studied as a succession of independent T-intersections, with only right-turn movements. In this case, performances evaluation could be measured by the following parameters:

- saturation index, that is demand flow divided by the entry capacity;
- mean delay that is the composition of waiting delay and geometric delay.

Whilst in the congested legs of roundabouts the entry capacity calculation requires an iterative process and so the solution is not so simple, in an under-saturation case the entry capacity evaluation is immediate applying the capacity formula.

Delays and queues

Delays and queues suffered by each entry lane are the third basic set necessary to complete a performances analysis.

The queue length for each approach leg depends on the inflow vehicles waiting to merge into the facility; they are the composition of vehicles that do not have entered jet and of new vehicles just come.

The mean delay on each approach leg depends on the inflow vehicles waiting to merge compared to the vehicles able to merge into the facility.

Entry capacity in an under-saturation case, delays and queues depend both on the O/D flow pattern and on the total entry flow for each leg (and so on circulating flows around the central island).

As it can be argued, the entry capacity is not a fixed value; of course, it depends on the geometrical features of the merge area, but it depends also on the circulating flow and on the entering traffic flow condition.

Many models have introduced some coefficients to correlate in the best way the entry capacity to the circulating flow. In some cases these coefficients depend on the geometry of the merge area, in some others on the entry and circulating lanes number, in some others on vehicles interactions: as a consequence, there is not a common and wide accepted criterion to the entry capacity formulation.

In the next section, the first steps of a different approach are reported. The entry capacity is correlated to the circulating flow on the basis of macroscopic parameters; the main idea is that these parameters depend only on the maximum flow that the circulating lanes and the entry lanes could manage (in other words, their capacity when there are respectively no entry flows and no circulating flows).

In such a way, the entry-circulating relationship could be managed referring to the physical capacity of the conflicting streams. This approach presents some advantages, which are:

- the capacity as a traffic parameter is well-known and easy to calibrate;
- capacity limitations are rightly present in the model and clearly visible.

THE PROPOSED APPROACH

Even if each roundabout facility could be divided into input, weaving and output segments, the critical element seems to be the input one where different traffic streams compete for space. Moreover, this element is always present while the other ones could be neglected (in small roundabouts, for example). As a consequence, the proposed methodology focuses mainly on merging areas.

In particular, the model presented in "Albanese–Camus–Longo" has been applied to describe traffic dynamics on merging areas inside roundabouts. This model has been originally developed to describe the behaviour of on-ramp lanes on a freeway facility: it may be considered as a mesoscopic model because it falls in the middle between the macroscopic approach of the Highway Capacity Manual and the microscopic approach proposed by the Gap-Acceptance theory.

The main idea is the utilization of the same methodology for the evaluation of the entry capacity and queuing dynamics on each roundabout leg. Referring to the paper in the References for a complete description of the model, here some features are briefly recalled.

Main definitions

According to the HCM procedure, the traffic streams are analyzed referring to a time step *t*, usually a fraction of hour to easily model peak phenomena. In the roundabout case, the mainline flow is the circulating one, whilst the on-ramp flow is the entry one on each approach leg.

Let *SD(t)* be the system demand and MI(*t*) the mainline input, ONRD*(t)* be the on-ramp demand and ONRI(*t*) be the minor inflow (on-ramp), SC be the mainline capacity when minor flow is null and ONRC be the minor stream capacity when the major is absent, MO1(*t*) be the maximum flow assigned to the major stream due to the presence of the minor inflow and ONRO(*t*) be the maximum flow assigned to the minor stream due to the conflicting main flow. Then, let MF(*t*) and ONRF(*t*) the outflows from the merge area for the mainline and the minor flow respectively. Moreover, the mainline capacity does not change across the merge area and of course MF*(t)* ≤ SC *and* ONRF*(t) ≤ ONRC.* Of course SC and ONRC depend upon geometric and functional features of the roundabout and they could be estimated according to HCM procedures.

Model description

The mainline capacity within the merge area could be divided into the capacity assigned to the two conflicting flows. In the model formulation, the portions of the mainline capacity assigned to the major and minor flow are named MO1(*t*) and ONRO(*t*) respectively.

The portion of the major flow capacity assigned to the minor flow could be quantified by a single macroscopic parameter, $\beta(t)$. $\beta(t)$ depends on the major flow volume and on the hypothesis about the yield relationship between the major and the minor flows (absolute priority or limited priority merge). So, according to the notations previously reported, the main idea of the model is the introduction of two time-dependent parameters, $\alpha(t)$ and $\beta(t)$: $\alpha = \alpha(ONRI(t))$, quantifies the mainline capacity reduction due to the minor flow influence, whilst $\beta = \beta(MI(t))$ quantifies the minor flow entry capacity reduction due to the major flow influence.

The β parameter is strictly dependent on the circulating flow; as a consequence, it reflects vehicles behaviour in the merge area at a macroscopic level (as the Gap Acceptance theory does by a microscopic level using many traffic parameters). Furthermore, the model includes the limited priority merge case: it could be modelled by the introduction of the parameter β_{min}; this parameter allows quantifying the residual minor flow entry capacity, even under high major flow volumes.

The model needs the definition of three parameters: the circulatory roadway and the approach leg capacities (SC and ONRC) and the β_{min} parameter which have to be carefully calibrated. If $\beta_{min}=0$, the major flow benefits the absolute priority.

The formulations for the β *(MI(t))* function follow the following equations:

$MI_{max} = SC - \beta_{min} * ONRC,$

$\beta(MI(t)) = 1 - ((1-\beta_{min})/MI_{max})*MI,$ *for* $MI(t) =< MI_{MAX};$

$\beta(MI(t)) = \beta_{min}$ *for* $MI(t) > MI_{MAX}.$

In accordance with the previous definitions, following equations hold:

ONRF(*t*) = MIN($\beta(t)$ *ONRC, *ONRI*(*t*));

MF(*t*) = MIN(SC - ONRF(*t*) ; *MI*(*t*)).

In the case of limited priority assigned to the major flow, some queues could develop on the circulatory roadway and the tail of the queue could reach the preceding merge area. Due to the small distance between successive merge areas in roundabouts, queues growth in the mainline could happen very easily: as an immediate consequence, the capacity of the roundabout could fall down immediately. Queue dynamics could be well-described using a short time interval length within an hour: a fraction of hour is recommended, i.e. 1 minute could be sufficient to model peak traffic conditions.

The graph below reports the complete model formulation for both the case of $\beta_{min}=0$ and $\beta_{min}>0$.

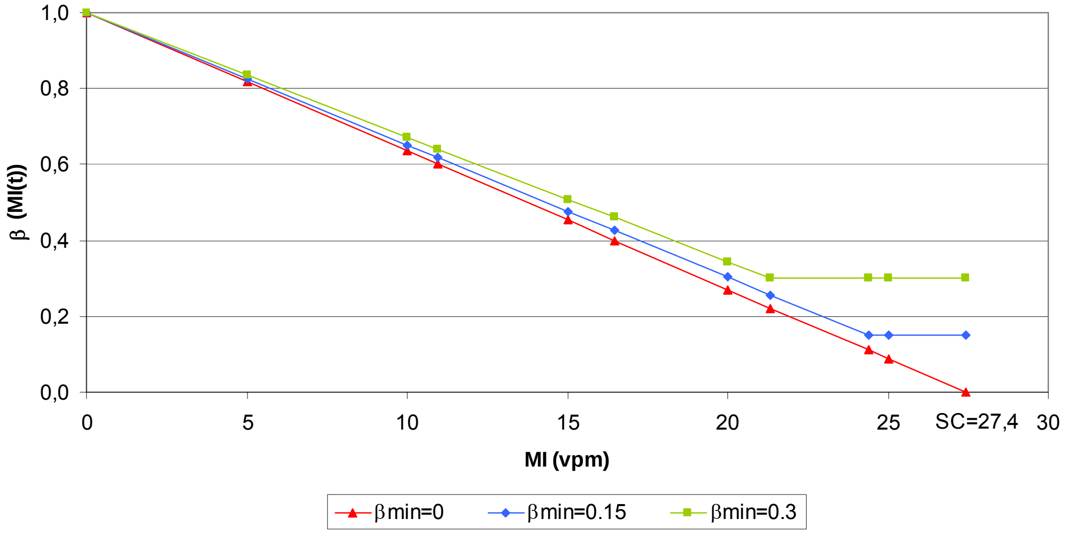

Figure 3: Proposed model, β(MI(t)) function

At this point, the model elaboration presents the same benefits of the first one; in addition, some other else which are:

- limited priority merge could be modeled and so the facility could be analyzed as a multi-junction node;
- capacity and level of service estimation needs only three macroscopic parameters;
- the model could be easily adapted to the major flow absolute priority condition;
- the parameter β is strictly connected to vehicles behavior;
- entry capacity prediction is very satisfactory.

On the other hand, the model could lightly overestimate the entry capacity. After a comparison between the predictions of the model compared to the predictions of the Gap Acceptance theory, it was found that reducing β_{min} values is equivalent to increase the Critical Gap value; in particular, $\beta_{min}=0$ is more or less equivalent to a three seconds Critical Gap. Vehicles waiting to merge in the major flow could sometimes need higher Critical Gap values, and that's why it is necessary to extend the model to a more general formulation; that is what follows in the next section.

The right assignment to the β_{min} value is the first step of the model. In order to further improved the model, it could be usefully extend to the following

- if $\beta_{min}>0$, limited priority merge case;
- if $\beta_{min}=0$, a three parameters model could be introduced (absolute priority case).

In this second case, these parameters are called β_{min}, m and γ; the two new parameters are necessary to reduce the β(t) function to the composition of two straight lines, intersecting at the point A (X_A;Y_A), as reported below.

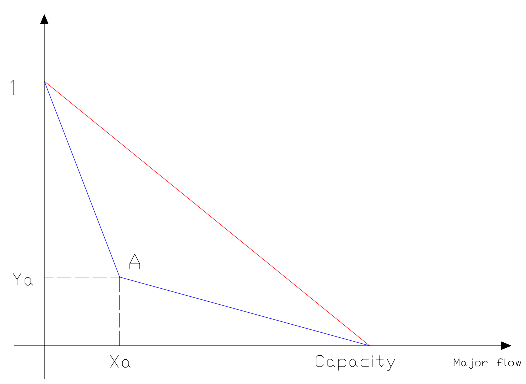

Figure 4: Proposed model, β(MI(t)) function for β_{min}=0

The coordinates of the point A depend on m and γ parameters, according to the following equations: $X_A = \gamma * SC$, $Y_A = m * X_A$.

The followings are the new formulations for the *β (MI(t))* function (for $\beta_{min}=0$):

$\beta(MI(t)) = MI(t)*(Y_A-1)/X_A+1$, for $MI(t) < X_A$;

$\beta(MI(t)) = Y_A*(1-(X-X_A)/(SC-X_A))$ for $X_A \le MI(t) \le SC$.

The last formulation of the model is the most complete one; the introduction of the three parameters formulation, allows the model to easily reproduce the same results by Troutbeck or Siegloch within the Gap Acceptance theory. Furthermore, in such a way, the model could be applied in many different traffic conditions and in well-accordance with the most reliable results of the scientific literature.

A careful calibration of the parameters β_{min}, m and γ could guarantee good results on both the entry capacity and the queue dynamics estimation; accordingly to the idea that they represent vehicles interactions, reducing m and γ values is equivalent to reduce the minor flow entry capacity.

The final elaboration of the model

The graph below reports the complete model formulation for both the $\beta_{min}=0$ and $\beta_{min}>0$ cases.

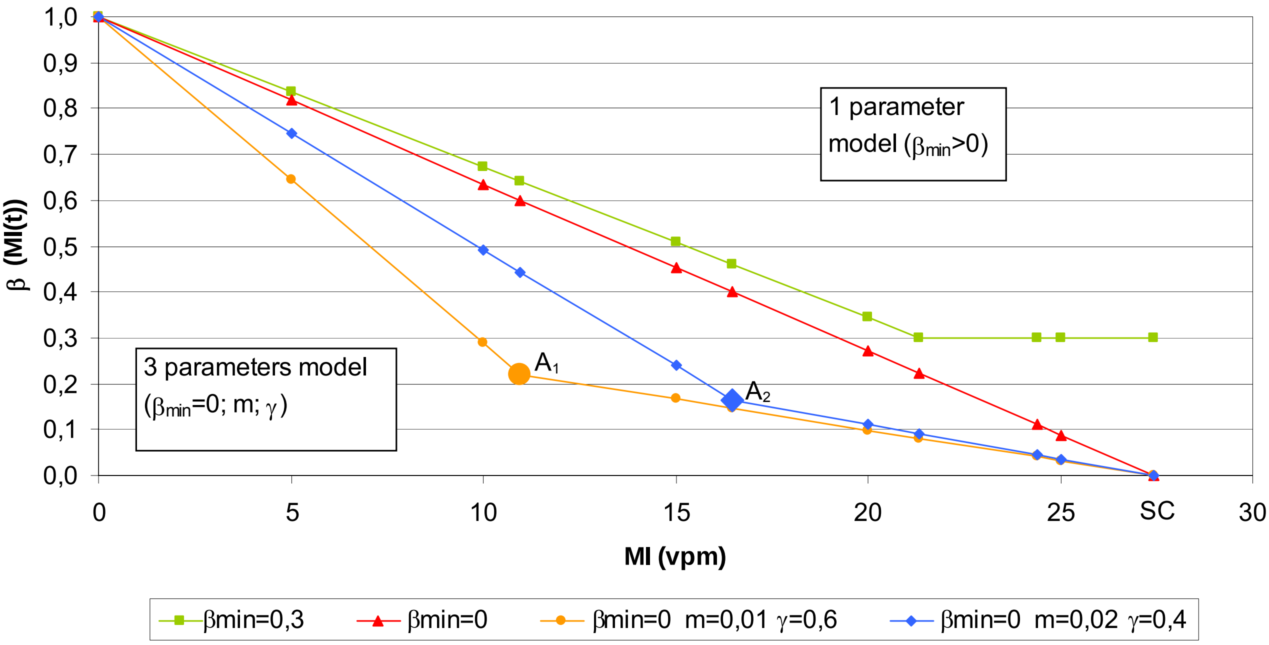

Figure 5: Proposed model, final elaboration, β(MI(t)) function

A very wide spectrum of traffic conditions could be covered by the model, both in the approach leg and in the circulatory roadway. In particular, queue lengths could be very easily quantified, also if there are over saturation conditions during the time interval set. This is a very important point, because many models developed for un-signalized intersections (and for roundabouts) evaluation, could not be used when the entry demand flow goes over the entry capacity (saturation index major than one). On the contrary, the proposed model could manage overflow conditions both on the roundabout's legs and on the circulatory roadway. Furthermore, the model could also measure the global capacity of the roundabout when all approach legs present queues. As a consequence, the model is able to give the well-known performance measures usually applied to the roundabouts evaluation case.

Now the problem is: which is the relationship between the results of the proposed model and the output of the existing ones? In other words, is the proposed model able to reproduce the results of the existing models simply by a useful calibration of its parameters?

In order to answer to these questions, the proposed model and some others existing ones have been applied in order to evaluate the capacity and the Level of Service of a single lane roundabout. Entry capacity and queuing evaluation have been made for each approach leg. Time interval step has been fixed in 1 minute.

PERFORMANCE ANALYSIS: A CASE STUDY

Some of the existing models and the proposed one have been applied to a single-lane four-leg roundabout. The meaning of the main geometric parameters is shown in the next figure together with the real dimensions reported in the next table.

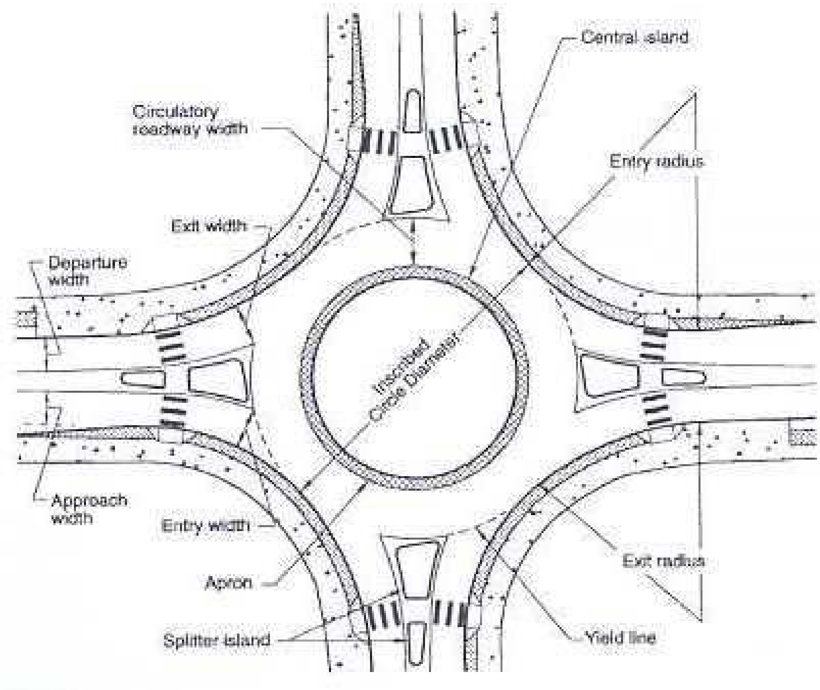

Figure 6: Geometric elements

Tab 3 – Case study: geometric values.

Design features	A eastbound	B northbound	C westbound	D southbound
Entry radius (m)	12	12	12	12
Entry width (m)	4	4	4	4
Approach width (m)	3.5	3.5	3.5	3.5
Exit radius (m)	12	12	12	12
Exit width (m)	4.5	4.5	4.5	4.5
Departure width (m)	3.5	3.5	3.5	3.5
Circulatory roadway width (m)	7			
Inscribed circle diameter (m)	35			
Apron (m)	0			
Splitter Island width (m)	7			

The following tables show the peak flows measured from the field; they were collected with a one minute time interval step, in order to model also congestion phenomena. It could be noticed that approaching flows are quite well balanced within the hour.

Tab 4 – Peak flows (vph)

O \ D	A eastbound	B northbound	C westbound	D southbound	Totals
A	0	419	174	104	697
B	110	0	515	110	735
C	327	131	0	262	720
D	228	285	171	0	684
Totals	665	835	860	476	

Some existing models have been applied to the case study. Entry flows have been grouped as one-hour flows; entry capacity values for models developed in different countries are given in the following table.

Tab 5 – Entry capacities for different models (vph)

	Macroscopic models			Microscopic models	
	Germany	France	England	Germany	Australia
A	783	739	847	755	836
B	884	800	919	861	926
C	977	893	986	963	1017
D	797	807	856	770	849
Totals	3441	3239	3608	3348	3629

Entry capacity values could be very easily evaluated in the following way. Given the demand flows and their origins and destinations, the circulating flows have to be firstly calculated; then the entry capacities on each leg could be calculated simply applying the entry capacity formula.
For example, the German linear model entry capacity formulation depends on the circulating flows (MI) and on two parameters (C, D):
ONRO = *C+D*MI* (vph).
If the circulating flow is known, then the entry capacity could be easily evaluated.

As showed by the tab 5, there are some differences on the total entry capacity predictions.
In addition, it has to be pointed out that the capacity evaluation procedure just described is not correct if some congestion phenomena (continuous queuing) are present in the merge areas. In other words, it is supposed that entry demand flows are lower than the entry capacity in each approach leg. As a consequence, if some entry demand volumes cause saturation in the merge areas, the entry capacity values have to be evaluated in a different way.
Usually peak volumes cause queues on the most critical approach legs and so a correct entry capacity evaluation needs a more complex analysis; in particular, it is necessary to reduce the time interval set to a fraction of hour, (i.e. one minute).
The model developed in England by Kimber (Kimber, 1980) could manage an over-saturation situation: delays estimation is correct but the procedure is not very simple. Delay evaluations by some other models are not really applicable if the entry demand flow overcomes the entry capacity (saturation index superior than 1) because the predicted delays increase to very high and unreal values.
The proposed model has been tested. Thanks to the formulation of the model, it is easy to study delays and queues lengths developments mainly referring to only two macroscopic parameters: they are the system capacity SC and the on-ramp capacity ONRC. The model analyzes the facility as a multi-junction node and so queues evolutions could be followed on each approach leg in detail and without approximations.
The proposed model adherence to existing models could be easily tested comparing the corresponding results. At the beginning the two parameters (SC and ONRC) have to be evaluated: once fixed the geometry of the roundabout, the two capacities SC and ONRC could be calculated using one of the existing capacity models.
For example, the entry capacity equation of the German linear model in the case of one single lane roundabout should be written as follows:
*ONRO = 1218 – 0,74*MI* (vph).
The ONRC value is given the ONRO value when the mainline flow (MI) is null whilst the SC value is given by the MI value when the ONRO is null.
Once obtained the values for the capacities SC and ONRC, the proposed model could be applied easily. The other important parameter β depends on circulating vehicles volume; on the other hand, its minimum value has to be assigned and it depends on the priority level between the major and the minor flow. A β_{min} value major than null means that entering drivers try to force their entry to the circulatory roadway, causing also the so-called “limited priority merge” phenomenon. The β_{min} value should be different varying the approach leg of the facility and it should also change if traffic conditions vary during the day; in this paper, the β_{min} value is assumed to be constant during the analysis period and on all the approach legs. The estimation of the required parameters is non a trivial task, and it should be performed starting from real observations. In the following, these parameters have been fixed in order to reproduce the results of the existing models.
Some models to evaluate un-signalized roundabouts performances have been tested; also the proposed model has been tested and all results have been compared. The analyzed methods have been both the German models and the English one; they belong to the Macroscopic approach and to the Microscopic one

and so the following results will be useful as a test to verify the proposed model adherence to existing models.
Main results are given below.
The table reports the predicted entry capacity for each approach leg. Capacity prediction by existing models could be easily reproduced as regards both the capacity of the whole facility as the capacity of each single approach leg. As a consequence, it seems that the proposed model allows reproducing the results of each existing approach simply by calibrating the parameters.
On the other hand, also queues estimation could be easily developed and this is one of the most important improvements due to the proposed model. Actually entry capacity and delays are calculated in a iterative way as necessary inside a multi-junction node (in particular when there is congestion in at least an approach leg).

Comparison with the German linear model

The model developed in Germany has been applied to the case study. In addition, the proposed model has been applied too, using the same capacity values (ONRC and SC) assumed by the German model. Main results are given in the following three figures and in the following table where the results referred to the German linear model are reported again for sake of simplicity and clearness.
The proposed model parameters (supposing the limited priority case) are the following ones:
System capacity (SC): 1646 vph;
On-ramp capacity (ONRC): 1218 vph;
β_{min} = 0,25.

Tab 6: Linear German model: results and comparison

	Entry lane capacity (vph)				Total capacity (vph)
	A	B	C	D	
Proposed model	789	877	969	784	3419
German model	783	884	977	797	3441

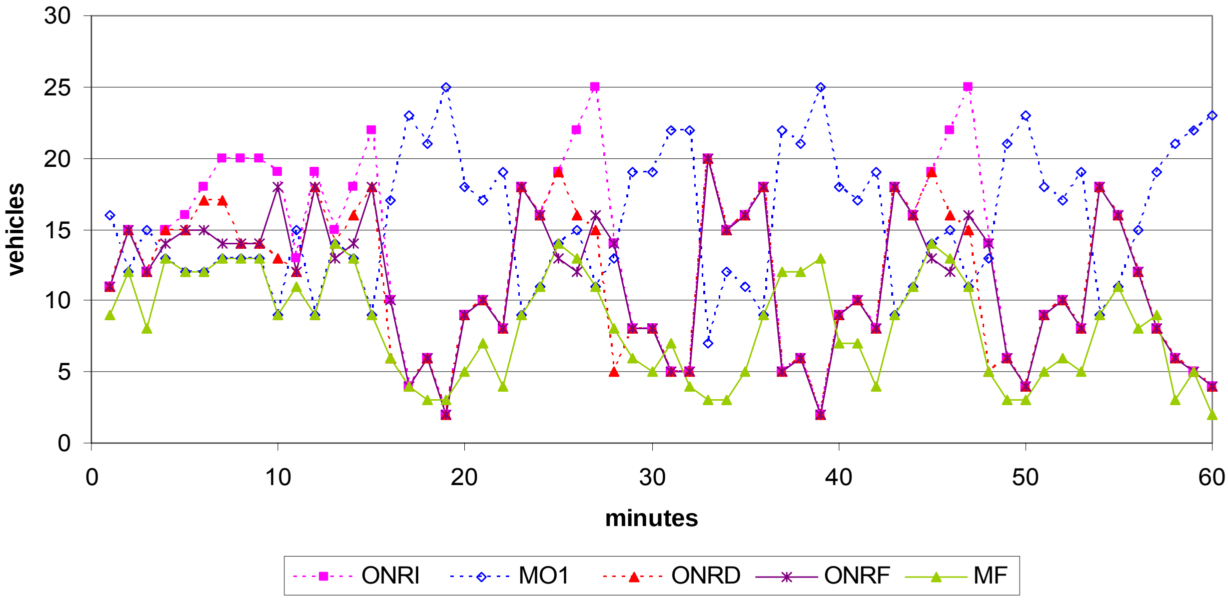

Figure 7: Leg D – Traffic flow pattern on the approach leg

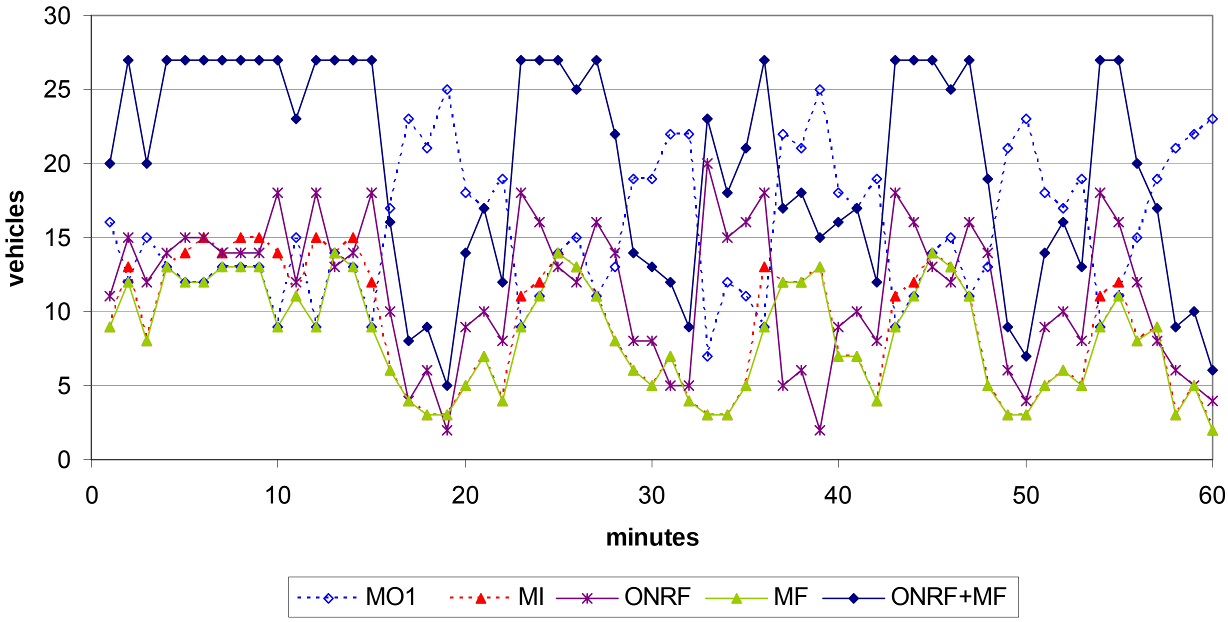

Figure 8: Merge area, approach leg D – Traffic flow pattern on the circulatory roadway

The figures 7 and 8 show two examples of the dynamic variation of flow patterns. In particular it is interesting to observe that the circulatory roadway capacity MO1(t) is not a constant value. Moreover the dynamic difference between the estimated in-flow pattern (ONRI(t) and MI(t) in figure 7 and 8 respectively) and the stream capacity (ONRF(t) and MF(t) in figure 7 and 8 respectively), if positive, represents the number of vehicles, which would like to transit along the facility but can not due to other preceding vehicles; it could be noticed that queue increases when the competitive flow is near to its capacity and vice versa.
The sum of ONRF(t) and MF(t) is limited from the circulatory roadway capacity; some queues could develop around the central island when there is not any reserve capacity to be used, and that is when the sum of ONRF(t) and MF(t) reaches the system capacity SC. This critical situation is clearly visible in figure 8 when the major flow capacity (MO1(t)) is equal to the major outflow (MF(t)): if the mainline volume (MI(t)) increases and goes over the mainline capacity, a queue begins to develop on the circulatory roadway just before the merge area (of course, in the limited priority case). Furthermore, if the demand flow ONRD(t) goes over the entry outflow ONRF(t), then some vehicles begin to queue also in the approach leg. The queue at the entry leg begins to reduce when the mainline outflow decreases below the mainline capacity MO1(t): in this case, there is a little reserve capacity on the circulatory roadway that could be used by queuing vehicles on the approach leg.
From these data it is quite easy to estimate both the dynamic evolution of queues and some other performances indicators such as the total lost time and the maximum queue length (see the figure 9 below). The total lost time in queue is given by the areas between the ONRI(t) line and the ONRF(t) line when the ONRI(t) line is above the ONRF(t) one. The maximum queue length (expressed in term of vehicles number) is given by the highest value of the on-ramp inflow ONRI(t).

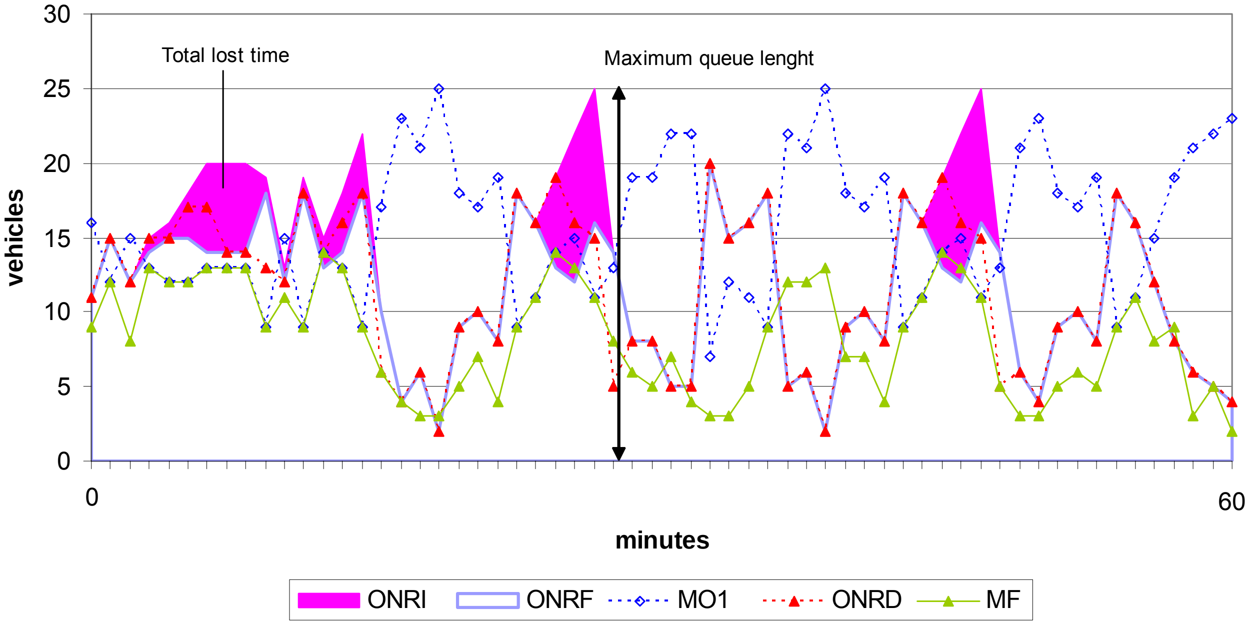

Figure 9: Leg D – Delays and maximum queue lenght

Comparison with the English linear model

The model developed in England has been applied to the case study. The proposed model has been applied too, using the same capacity values (the ONRC and the SC) assumed by the English model. Main results are given in the following figures and in the following table where the results referred to the English model are reported again for sake of simplicity and clearness.

The parameters of the new model (supposing the limited priority case) are the following ones:

System capacity (SC): 2183 vph;

On-ramp capacity (ONRC): 1160 vph;

$\beta_{min} = 0{,}1$.

Tab 7: English model: results and comparison

	Entry lane capacity (vph)				Total capacity (vph)
	A	B	C	D	
Proposed model	850	913	978	856	3597
English model	847	919	986	856	3608

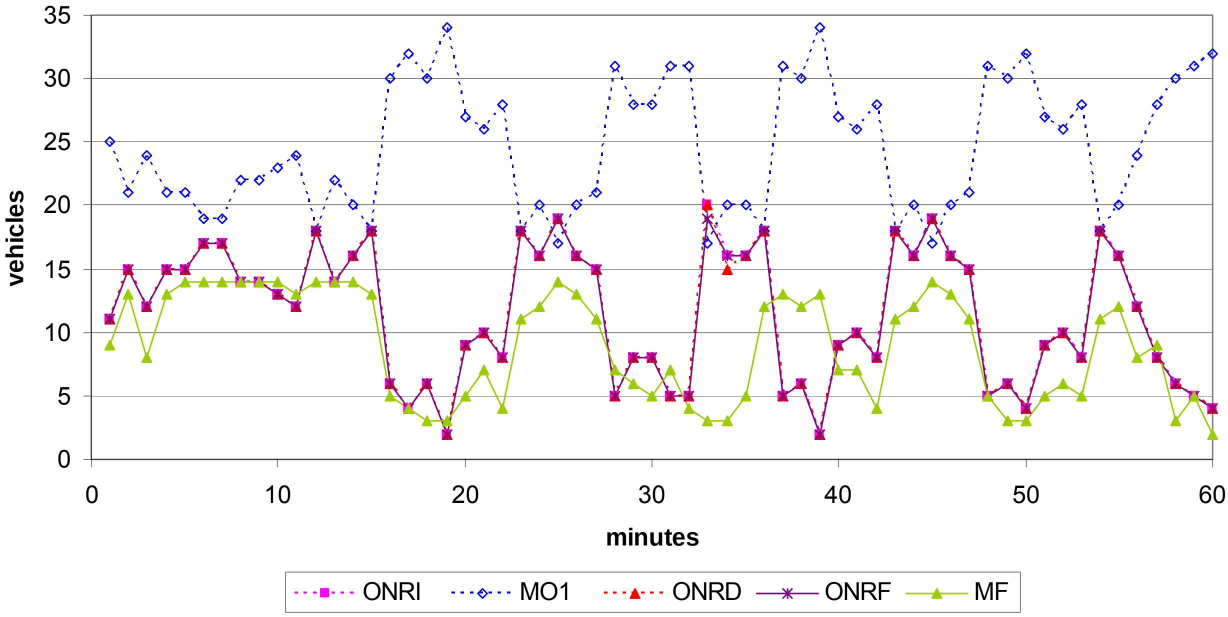

Figure 10: Leg D – Traffic flow pattern on the approach leg

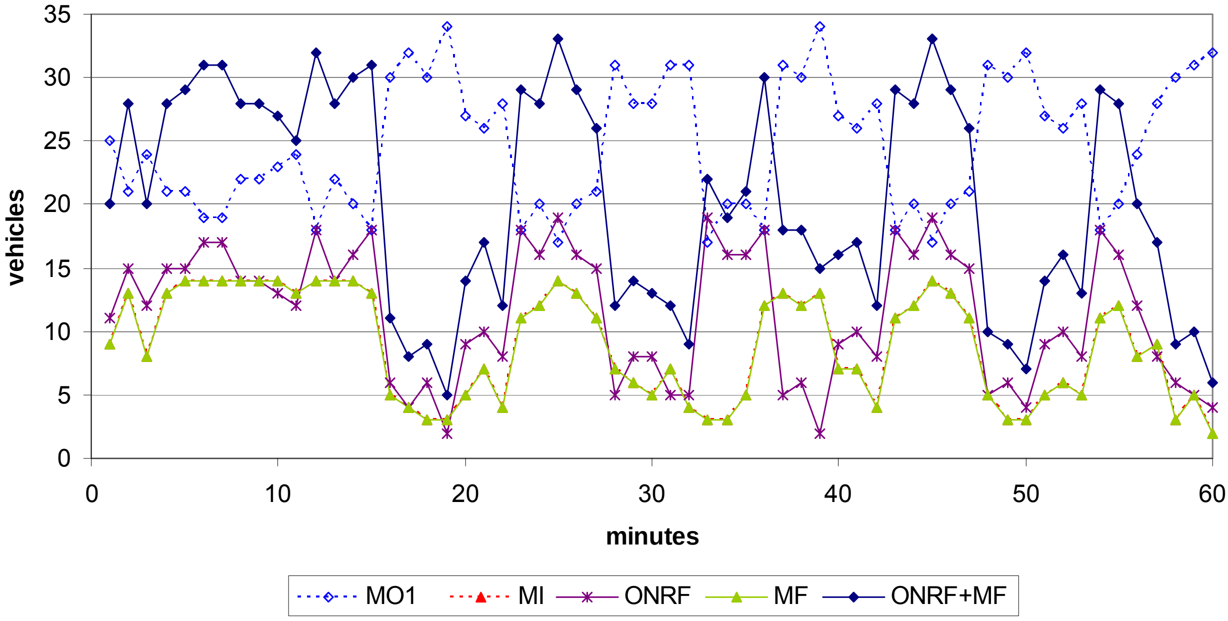

Figure 11: Merge area, approach leg D – Traffic flow pattern on the circulatory roadway

If the English model is applied, the system capacity SC and the entry capacity ONRC assume very high values if compared to the German models. As a consequence, very short queues could develop on the approach leg (see figure 10) and none queue develops on the circulatory roadway (see figure 11); in this case, the facility could manage the traffic flows without any problems, and no congestion phenomena are supposed to interest neither the approach leg nor any merge areas on the circulatory roadway.

The proposed model adherence to some macroscopic models has been usefully tested. In the next section the proposed model is applied and results are compared to the results of a probabilistic model.

Comparison with the German exponential model

The model developed in Germany following the Gap-Acceptance theory has been applied to the case study; in addition, the proposed model has been applied too, using the same capacity values (ONRC and SC) assumed by the German microscopic model. Main results are given in the following figures and in the following table where the results referred to the German exponential model are reported again for sake of simplicity and clearness.

The proposed model parameters (supposing the limited priority case) are the following ones:
System capacity (SC): 1714 vph;
On-ramp capacity (ONRC): 1250 vph;
$\beta_{min} = 0$.

Tab 8: German exponential model: results and comparison

	Entry lane capacity (vph)				Total capacity (vph)
	A	B	C	D	
Proposed model	775	861	968	792	3396
German model	755	861	963	770	3348

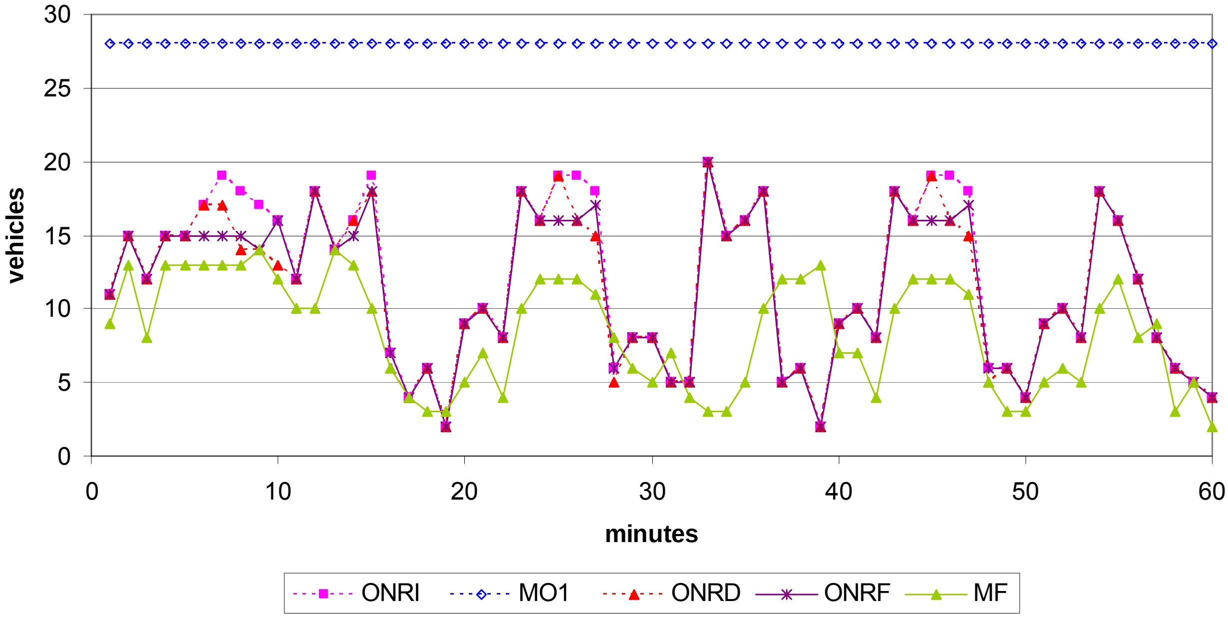

Figure 12: Leg D – Traffic flow pattern on the approach leg

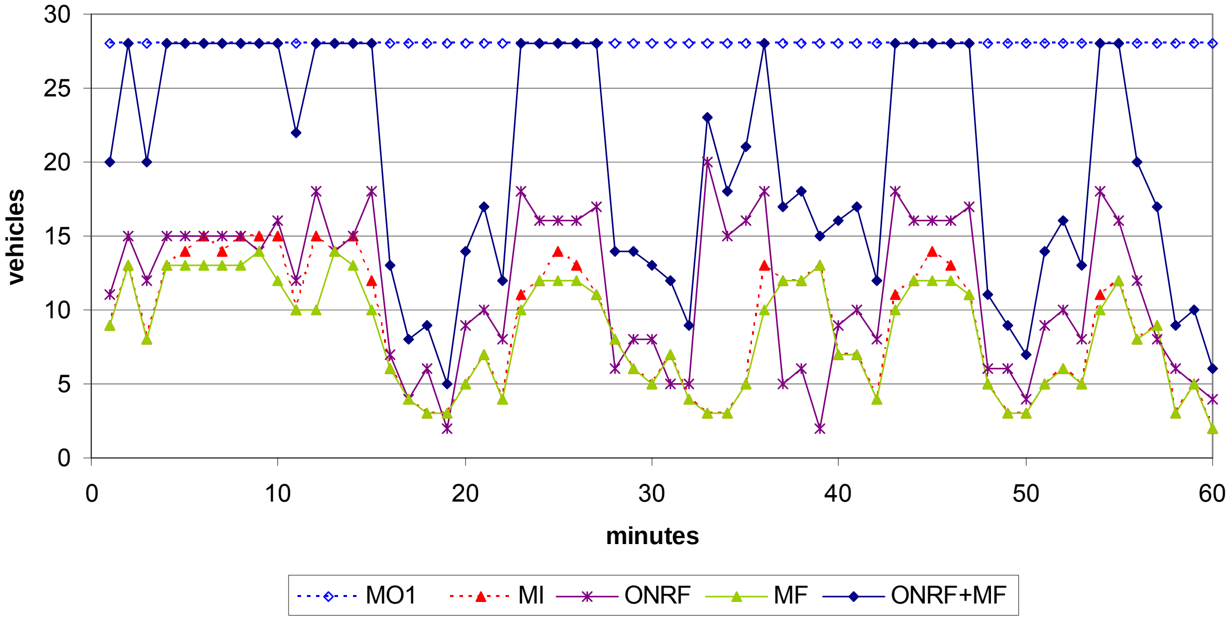

Figure 13: Merge area, approach leg D – Traffic flow pattern on the circulatory roadway

When the capacities SC and ONRC of the German exponential model are used within the new model formulation, the hypothesis of absolute priority to the major flow seems to be the best one. The new model gives good results also if compared to a microscopic model. In the case of absolute priority to the major flow, the major flow capacity MO1(t) is a constant value and no queues could develop around the central island; on the other hand, some queues could begin on the approach legs when the minor outflow ONRF(t) decreases below the on-ramp demand ONRD(t).

CONCLUSION

The paper reports some first results of a new model for the evaluation of un-signalized roundabouts. The proposed analysis refers mainly to the entry capacity and queue length estimation. The development of an original approach for the analysis of roundabouts seems to be necessary to overcome the uncertainty in the evaluation of these kind of intersections.

In this context, the methodology described in the paper could be considered a general framework (within many different models) to perform a complete evaluation of roundabouts, because:

- it is in accordance with the HCM main principles regarding the merge area analysis; at the same time, the methodology is also in well accordance with the Gap Acceptance theory, which is the well-known theoretical approach for the un-signalized intersections analysis;
- comparative results show that the new approach could easily cover capacity predictions by both the two German models (the linear model within the macroscopic approach and the exponential model within the microscopic approach) and by the model developed in England, with reference to both the global capacity of the roundabout and to each single approach entry capacity.

Moreover, the model could approach in a more complete way the Level of Service analysis problem, predicting queue length dynamics under both light and heavy traffic conditions. This is a very important result, mainly because many delays and queues prediction formulations within existing models are not suitable in congested conditions.

On the other hand, at present the results of the new model are in well-accordance with the results of existing models because the two capacity values SC and ONRC introduced in the new model are the same. On the contrary, if the new model, once fixed the traffic volumes and the geometry of the facility, is applied with different SC and ONRC values, it gives different entry capacity predictions.

In order to overcome this inconsistency, the first necessary step within the necessary further developments will be the definition of the SC and ONRC values using a general procedure suitable to yield controlled intersections and not specifically related to the roundabout evaluation case.

The new model has been described in all its parts. At this point, the model (in particular the $\beta(t)$ function formulation and the related parameters) allows the model to agree with main results obtained by Troutbeck on the entry capacity evaluation. The necessary next step will the calibration of the parameters introduced in the model, with reference to real data and focusing in particular to the measurements of entry flows, queues lengths and flows distribution matrix.

Also the relationships between the model parameters and the geometrical and functional features of each roundabout merge area should be further investigated for both a correct evaluation of the capacity values (SC and ONRC) and of the same parameters values.

Finally a possible third research step will be the average delay estimation for each vehicle grouped by entry and exiting leg (O/D flows). The main part of the total delay is given by queuing delay on small single-lane roundabouts, but on multilane roundabouts also the geometric delay has to be included in the total delay computation. In such a case, it should be necessary to include also the weaving and diverging movements for a more complete roundabout's performances analysis.

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