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# Automated identification of fastest vehicle paths at roundabout

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## Abstract

The geometric design of a roundabout follows an iterative process that aims at achieving an optimal balance between safety provisions, operational performance, and large vehicle accommodation. Evaluation of safety involves checking speed consistency along the vehicle paths, which requires identifying the trajectories of the fastest vehicles and the speeds at which they travel. A systematic procedure to identify the fastest vehicle paths for all possible movement types between the approaches of a roundabout by using as input data the roundabout geometry and the minimum distance between the vehicle and the roundabout edge is proposed. The determination of the fastest path between an entry and an exit is based on the generation of multiple feasible paths and the final selection of the fastest one. The proposed procedure supports the safety assessment of a roundabout geometric design according to most relevant international guidelines and can be easily implemented in a heuristic roundabout design procedure. The application of the method to a trial case is presented to demonstrate its performance and applicability.

CE Database subject headings: Highway design; roundabout; fastest path; speed consistency

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# INTRODUCTION

A roundabout is an intersection in which an annular roadway connects the approach legs and traffic entering the roundabout must yield to traffic in the roundabout. The design of a roundabout aims at achieving a good balance between safety, operational performance, and large vehicle accommodation. The design is usually developed in two stages taking as starting data the surrounding conditions, the largest vehicle that is expected to travel through the roundabout, and the capacity requirements to serve the traffic demand at each roundabout entry.

At the first stage, the designer selects the type of roundabout between single-lane and multilane and estimates its size. Single-lane roundabouts have a single lane entry at all the legs and one circulatory lane, while multi-lane roundabouts have at least one entry with several lanes. In this case circulatory roadways have to accommodate more than one vehicle traveling side by side. The size of a roundabout is characterized by its inscribed circle diameter.

The second stage is an iterative process which begins with the definition of a trial geometric design of the roundabout using a set of suitable values for the key geometric elements following the recommendations of the applicable guidelines. The trial design must be subsequently checked to confirm that it meets the overall design objectives. Design engineers commonly perform these checks using computer aided design (CAD) tools. Because minor adjustment in geometry can result in significant changes in the safety and/or operational performance, several iterations are usually required until a satisfactory design is achieved.

Traffic safety at roundabouts depends largely on the speeds at which drivers approach to the entries and on the speeds at which they pass through the roundabout. Risk increases not only with speed, but also when a driver needs to reduce his speed abruptly. As a consequence, the safety check involves the analysis of the speeds at the roundabout and its approach legs and of their gradients. At rural roundabouts, high approach speeds are usually present, so good approach visibility of the central island and the general shape of the roundabout is desired to make drivers aware of its presence and provide ample distance to decelerate comfortably. At urban environments the presence of pedestrian and bicyclist is frequent, and lower speeds are usually desired, in addition to providing adequate facilities for them. In the design of a roundabout, the circulating speed can be controlled by adopting a geometry that constrains the vehicles to travel along a curved path. A greater curvature of a vehicle path results in the reduction of speed, which consequently improves safety provided that the approach speed has been previously reduced. Nevertheless, it may deteriorate traffic operation and capacity.

The search for a design with safe circulating speeds involves making iterative modifications of the roundabout geometry, determining the trajectories of the fastest vehicles and the speed at which they travel, and, finally, evaluating safety conditions. For this purpose, the fastest paths for all approaches of the roundabout need to be identified. For each specific entry and exit, the fastest path can be defined as the smoothest, flattest path possible for a single vehicle traversing through the entry, around the central island, and out the exit in the absence of other traffic and ignoring all lane markings (Rodegerdts et al. 2010).

For determining the fastest paths, various procedures to draw the potential trajectories either manually or with the assistance of CAD programs have been proposed (Rodegerdts et al. 2010). In any case, the construction of the fastest paths is often a subjective process requiring a certain amount of personal judgment. To solve this, alternative methods to identify the fastest paths in a systematic way with the assistance of automated algorithms have been developed. However, thus far none of them has solved the problem completely for all the possible types of movements. To address this gap, this article introduces a new method that uses the roundabout geometry and the minimum distance between the vehicle and the roundabout edge as input data. This method can be easily implemented in a heuristic roundabout design procedure (Rubio-Martín et al. 2014) where the paths are computed using the methodology described in the present article. The application of the method to a study case is presented to demonstrate its potential to support the design evaluation process.

## BACKGROUND

In practice, the geometric design of a roundabout is performed as an iterative process that aims at achieving an optimal balance between large vehicle accommodation, operational performance, and safety provisions. Each design trial must be checked for the three conditions.

To ensure large vehicles accommodation it is checked that the geometry allows the turning maneuvers of the design vehicle. This type of check can be performed using appropriate vehicle turning templates (AASHTO 2011) or a CAD-based vehicle turning path program to determine the vehicle's swept path (Godavarthy et al. 2016). To avoid a too wide circulating roadway, a truck apron may be used to provide additional traversable area around the central island.

Operational performance is evaluated at each entry in terms of queues and delays depending on entry capacity and approach volumes. Entry capacity depends on several factors related to the geometric layout of the roundabout, the environment in which it is located (rural or urban), and the distribution of the traffic flows inside the roundabout. The geometric layout allows the designer to control the capacity (Yap et al. 2015). To estimate roundabout capacity different models have been developed in several countries based either on empirical approaches (that yield direct geometric relationships to capacity) or gap-acceptance approaches (which consider the driver behavior, using the critical gap and follow-up time) (Ren et al. 2016). These models are usually incorporated into national design guidelines.

The last main check of the geometric design refers to safety conditions. Accidents at roundabouts are frequently related to conflict points (vehicle-vehicle, vehicle- pedestrian or vehicle-bicycle). Their severity depends on the relative speeds of the vehicles and on the collision angle. In addition, excessive entry speeds may result in loss of control of the vehicle and originate run off the road crashes. The evaluation of safety at roundabouts may be undertaken using either accident data or surrogate measures such as traffic conflict analysis (Sadeq and Sayed 2016).

Most existing roundabout safety analysis has focused in establish a relationship between contributory factors and crash rates.  Major crash causative factors are related to geometric design and traffic conditions (Kennedy et al. 2005; Montella 2011; Anjana and LR Anjaneyulu 2014). However, there is widespread recognition of operating speed as a key safety-related variable for roundabouts (Chen et al. 2013). Several researchers proposed the use of predicted vehicle speeds instead of roundabout geometric variables for estimating safety performance (Arndt and Troubeck 1995; Robinson 1998; Chen et al. 2013). Therefore, predicting the speed at a roundabout as a function of the intersection geometry is fundamental in the design process (Gallelli et al. 2014).

Safety evaluation based on conflict analysis has the disadvantage that it is not clear the linkage between traffic conflicts and collisions (Sadeq and Sayed 2016). In addition, some accident types such as run-off-road crashes cannot be correlated with conflict types because they cannot be observed in conflict analysis.

Different countries have developed extensive design guidelines and methods to evaluate the performance of roundabouts (Rodegerdts et al. 2010; Austroads 2015; SETRA 1998; QDMR 2006; Highway Agency 2007; MF 2012). Most design guidelines provide criteria for controlling circulating speeds through roundabouts based on geometric parameters of the vehicle paths or the roundabout such as the radius of deflection, the entry path radius, and the deviation angle (Montella et al. 2012).

The entry path radius is a measure of the deflection imposed on vehicle trajectory when entering a roundabout. Its effect on the safety of a roundabout design has been proven in several studies (Maycock and Hall 1984; Arndt 1998). The UK design manual recommends a maximum entry path radius of 100 m (Highway Agency 2007).

The radius of deflection corresponds to the arc that defines the path around the central island. Both the Queensland (Australia) and the French design guidelines suggest limiting the radius of deflection to less than 100 m (SETRA 1998; QDMR 2006).

The definitions of both the entry path radius and the radius of deflection require identifying the fastest vehicle paths from the geometry of the roundabout. The deviation angle is the angle imposed by the central island between two opposite entrances. Sound designs should have a deviation angle greater than 45° for all the entries (VSS 1999; MIT 2006). The computation of this indicator is based solely on the geometry of the roundabout.

Other design guidelines base the safety checks directly on speeds (Rodegerdts et al. 2010; Austroads 2015). The collision risk between two vehicles can be reduced by designing a geometry that provides a low relative speed of the conflicting flows, and the accident risk of an isolated vehicle can be reduced with a geometry that avoids large speed reductions along a vehicle path (Arndt 1998). From a practical point of view these risks are evaluated using the concept of speed consistency. Consistency is the relationship between the geometric characteristics of a highway and the conditions a driver expects to encounter (Lamm et al. 1999). It is usually measured on the basis of operating speed gradients. According to Arndt (1998) achieving a good speed consistency at a roundabout, which results in enhanced safety, has two implications: first, the relative speeds between consecutive geometric elements at each particular path have to be minimized; and second, the relative speeds between conflicting traffic streams should be as well minimized. Arndt (1998) recommends a maximum decrease in speed of 20 km/h for a particular path and a value that ranges between 35 and 50 km/h for conflicting paths depending on the characteristics of the conflicting point. More recently, Rodegerdts et al. 2010 suggest that maximum speed differential between movements should be no more than approximately 15 to 25 km/h.

Speed consistency analysis requires the identification of the fastest paths and their associated speeds. The Australian evaluation procedure (Austroads 2015; Arndt 1998) is based on the definition of all the fastest vehicle paths and their speed profiles except the movement from an entry and the consecutive exit (right turn in right-hand driving countries). The US guidelines (Rodegerdts et al. 2010) proposes the determination of the fastest vehicle paths of the through movement, the left-turn movement and the right-turn movement from each approach, but suggests the selection of five critical arcs from these paths to be subsequently used in the speed consistency evaluation. A similar methodology has been adopted in Spain (MF 2012).

In multi-lane roundabouts, multiple traffic streams may enter, circulate through, and exit the roundabout. As consequence, in addition to determining the fastest paths and evaluating the speed consistency as in the case of single-lane roundabouts, assessment of the natural vehicle paths takes special importance. In the case of multi-lane roundabouts, it is assumed that a natural vehicle path is the path that an approaching vehicle will naturally take through the roundabout assuming there is traffic in all the approach lanes (Rodegerdts et al. 2010). If the natural path of one lane overlaps with the natural path of the adjacent lane the roundabout capacity and safety conditions are diminished. To avoid this situation, it is desirable that the natural paths do not have sudden changes in curvature and that consecutive curves be of similar radius. The larger size of multi-lane roundabouts and the larger width of the circulatory roadway originate larger radii of deflection of the paths, which leads to the need for larger entry and exit radii to avoid the overlapping of natural paths. In consequence, it may be difficult to keep the radii of the entry paths below a value that forces vehicles to enter the roundabout at a safe speed and so ensuring speed consistency at multi-lane roundabouts is more difficult than in the case of single-lane roundabouts.

Several approaches have been proposed to estimate the operating speeds from the fastest vehicle paths allowed by the geometry. Operating speed is usually represented by the 85th percentile (V85) of the distribution of observed passenger vehicle speeds under free flow conditions. At roundabouts, operating speeds can be obtained from the fastest paths using the following relationship between horizontal curvature, travel speeds, superelevation and side friction factor, which is provided from vehicle dynamics:

$$V = \sqrt{127 \cdot R \cdot (e + f)} \qquad (1)$$

where

$V$ = predicted speed, km/h;

$R$ = radius of the circular arc, m; and

$e$ = superelevation, m/m.

f= side friction factor

Typical superelevation values of +0.02 and −0.02, corresponding to 2% cross slope, are usually considered at roundabouts. The value of the side friction factor depends on speeds and highway geometric design guidelines usually provide its reference values as a function of the design speed (MF

2012; AASHTO 2011; FGSV 2006). Based on US reference values, Rodegerdts et al. (2007) proposed the following relationship between speed and horizontal curvature at vehicle path, which has provided good correlations with real data when combined with acceleration and deceleration factors.

$$\begin{aligned} V &= 8{,}7602 \cdot R^{0{,}3861} \quad \text{for } e = +0{,}02 \\ V &= 8{,}6164 \cdot R^{0{,}3673} \quad \text{for } e = -0{,}02 \end{aligned} \tag{2}$$

Roundabout design guides generally recommend that the fastest paths be built as a series of circular arcs linked by tangent straight lines, while maintaining certain distances or offsets to some elements of the roundabout. For example, the US guidelines (Rodegerdts et al. 2010) proposes that the fastest vehicle paths be estimated assuming a vehicle width of 2 m and a minimum clearance of 0.5 m from the roadway centerlines or concrete curbs as well as that the vehicles keep flush with the painted edge lines. Based on these assumptions, the centerline of the vehicle path is drawn maintaining the following distances to particular geometric features: 1.5 m from a concrete curb, 1.5 m from a roadway centerline, and 1.0 m from a painted edge line.

Making use of offsets, the fastest paths can be obtained by using templates to draw freehand successive trial solutions until a satisfactory one is achieved. This process is slow and laborious. In addition, it does not converge to a single common solution, as it depends on the personal judgment of each designer. To facilitate this task, CAD programs are used. For example, Wisconsin Guidelines (WisDOT 2008) propose a set procedure for creating the fastest paths in CAD. However, the task remains partially manual and time consuming.

At a local level, the Ada County Highway District in Idaho (US) developed a Roundabout Design Guide (ACHD 2011), including a method that allows the computation of the radii of the five critical arcs as recommended by the US guidelines. The procedure first determines the exit type based on the number of entry lanes and the flatness of its exit geometry; then, depending on the exit type, a procedure is selected from three alternatives, and the fastest path is calculated using simple geometric constructions. This method can be automated. However, when the angles between consecutive legs are large, this method cannot determine the fastest path.

Existing methodologies only provide partial solutions to the computation of the fastest paths. In this article, a new procedure is proposed for the computation of the fastest paths in a systematic way that overcomes this drawback.

## METHODOLOGY

In the proposed methodology, to determine the fastest path between an entry and an exit, the geometry of the roundabout along with some constraints regarding the minimum distances that the vehicle has to maintain with the edges of the roundabout are taken as input data. This section starts with the description of the geometric elements that define a roundabout, which can be automatically drawn from a set of scalar variables. Next, a set of auxiliary geometric elements that are used for considering the constraints in the path definition process is described.

The proposed methodology, which is applicable indistinctively to one-lane or multi-lane roundabouts, classifies the possible paths between an entry and an exit into two categories: “direct path” or “deflected path”. The characteristics of these categories are explained, and the use of circular arcs and tangents is suggested for their definition. Next, a procedure is proposed for the geometric construction of direct and deflected paths, taking as starting data the geometry of the roundabout, the auxiliary geometric elements, and two or three reference points located at the entry, at the exit and at the circulatory roadway.

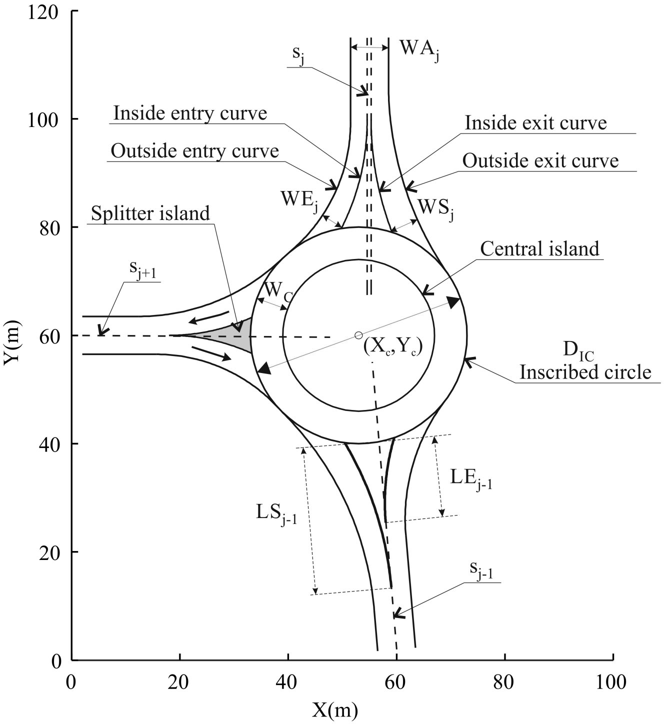
Finally, as different solutions can be reached for a path depending on the exact position of the reference points, a procedure is proposed that allows selecting the fastest path among the group of potential solutions that have been generated according to the constraints they should meet and using different positions of the reference points.

### Geometric description of a roundabout

The design of a roundabout often takes the alignment of the approach legs as the starting input. Next, the geometry of the circulatory roadway and that of each approach leg are defined. The circulatory roadway is described by the inscribed circle diameter $D_{IC}$, the coordinates of its center

(Xc,Yc), and its width $W_C$. Each of the approach leg is described by its alignment *s* and the entry and exit curves (Fig. 1).

The geometry of an approach leg can be fully drawn according to the roadway approach width (*WA*), the entry and exit splitter island lengths (*LE* and *LS*), and the entry and exit widths (*WE* and *WS*). Rubio-Martín et al. (2014) proposed a procedure assuming that the geometric design of either an entry or exit use a single curb radius: the outside entry–exit curve is an arc of circumference tangent to the outside edge of the circulatory roadway and the edge of the approach leg; the inside entry–exit curve is an arc of circumference tangent to the central island and the axis of the approach leg. The entry and exit curb radii can differ, but both are controlled by the value of the entry and exit splitter island lengths. This procedure is typically suitable for single-lane roundabouts (Rodegerdts et al. 2010) but is also applied in multilane roundabouts or when the approach leg presents a narrow median.



**[Fig. 1 Approximately here]**

## Geometric constraints in path definition

When defining the paths, the vehicle width has to be selected and a minimum clearance from the roadway centerlines, concrete curbs, or painted edge lines must be maintained. In the proposed methodology, the following variables are used to consider these constraints in the path definition (Fig. 2):

$d_1$ (m): minimum distance from the path to the approach leg axis (or the median edge if it exists) and the inside entry curve.

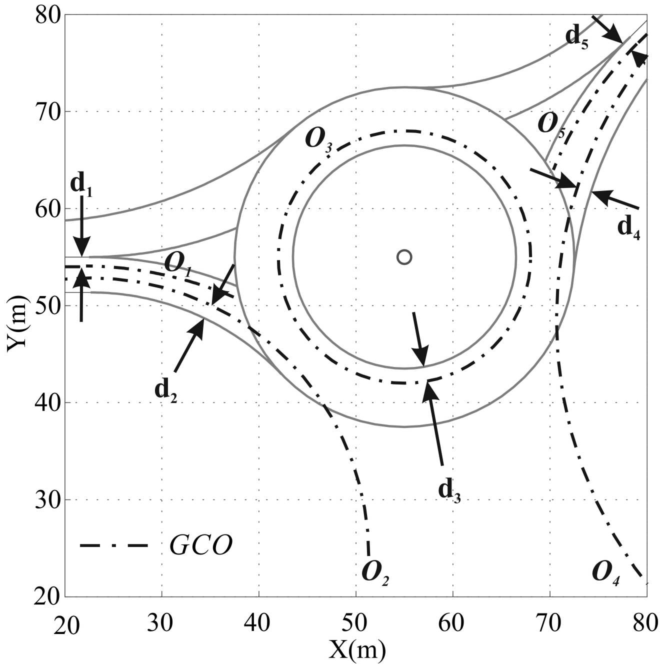
$d_2$ (m): minimum distance from the path to the outside entry curve.

$d_3$ (m): minimum distance from the path to the central island (or the truck apron if it exists).

$d_4$ (m): minimum distance from the path to the outside exit curve.

$d_5$ (m): minimum distance from the path to the exit leg axis (or the median edge if it exists) and the inside exit curve.

These variables can be estimated on the basis of the vehicle width and the existence of concrete curbs, medians, or truck aprons. The US guidelines (Rodegerdts et al. 2010) provide approximate values for them. Once an entry and exit are selected for the determination of the path between them, five alignments (geometric objects) $O_i$, $i = 1,\ldots,5$, need to be defined as illustrated in Fig. 2. These alignments are parallel to the roundabout geometric elements at an offset of $d_i$, $i = 1,\ldots,5$. They are later used in the definition of the path between the selected entry and exit and are, hereinafter, called "Geometric Constraint Objects (GCO)" in order to facilitate the explanation of path computations. Hereinafter, a path is referred to as "feasible" when it satisfies all the constraints and "infeasible" otherwise.

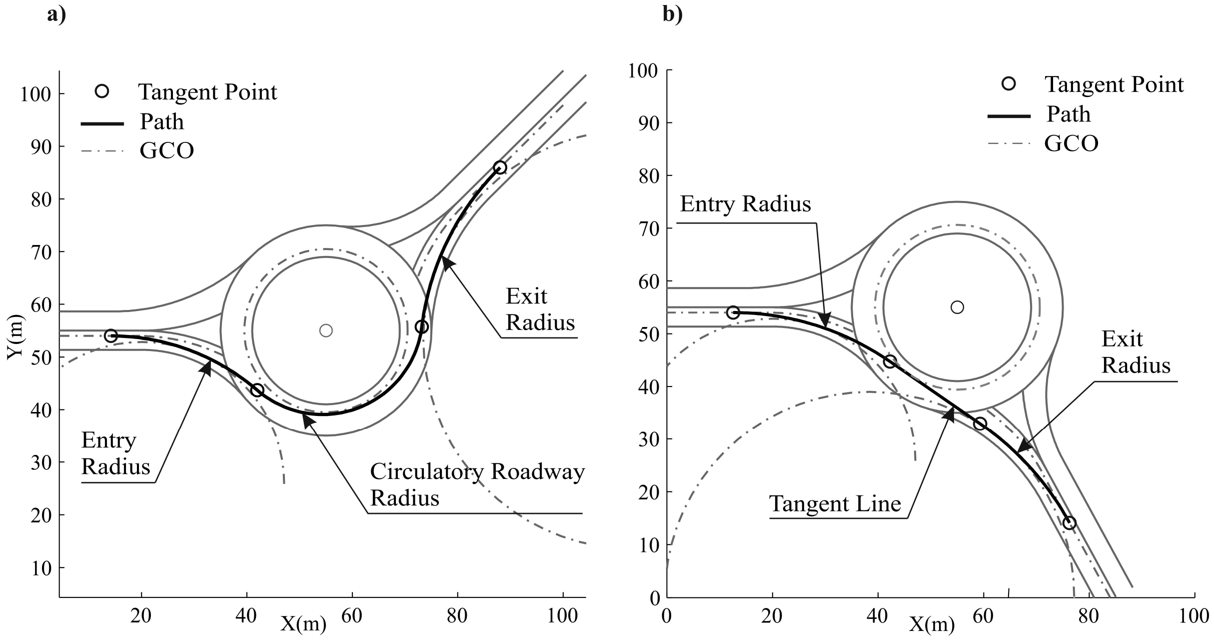


**[Fig. 2 Approximately here]**

### Path classification

A driver entering a roundabout can select various exits. International design guidelines commonly classify the possible movements from an entry to an exit into three types: right-turn, left-turn, and through movement depending on the relative positions of the entry and the exit legs.

In the proposed methodology, a new classification of the paths is used, namely, "deflected path" and "direct path". A deflected-path is followed when the central island imposes two inflexion points in the vehicle path around the roundabout. A direct-path is followed in the absence of any inflexion point in the vehicle path (Fig. 3).



**[Fig. 3 Approximately here]**

A deflected path is built with three consecutive and tangent circular curves, with the second one having opposite sign to the other two. The radii of these circular curves are called “entry radius,” “circulatory roadway radius,” and “exit radius” (Fig. 3a). A direct path is built with a circular curve at the entry, a circular curve with the same sign at the exit, and an intermediate straight line tangent to the curves (Fig. 3b). In some situations, this line can be reduced to a point. This procedure of computing a path is aligned with the recommendations of international guidelines.

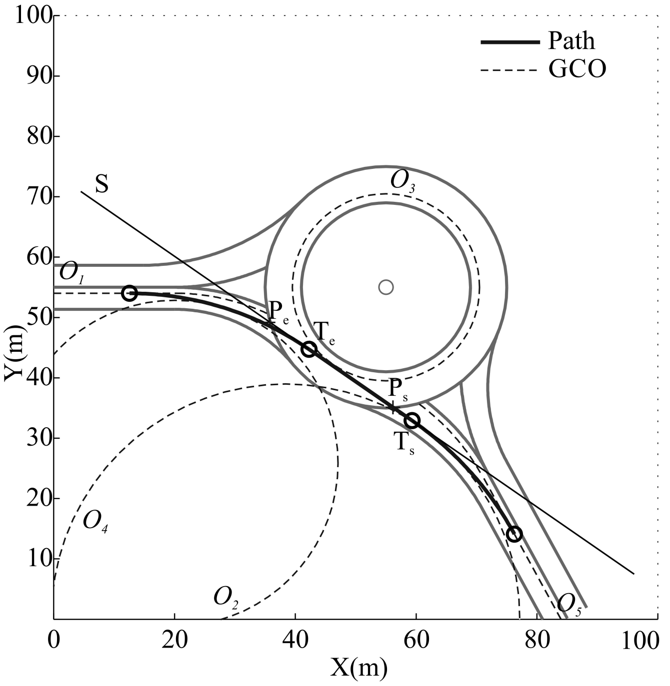
## Definition of a path

A path between an entry and an exit is built as a series of circular arcs tangent to each other with the condition that it be tangent to the GCO and passes near (sometimes through) a predefined set of points. For a direct path, two points $P_e$ and $P_s$ located at the entry and the exit are used. Additionally, a deflected path must pass through a third point $P_c$ located at the circulatory roadway. These points and the GCO are taken as the starting data to compute the path as described below.

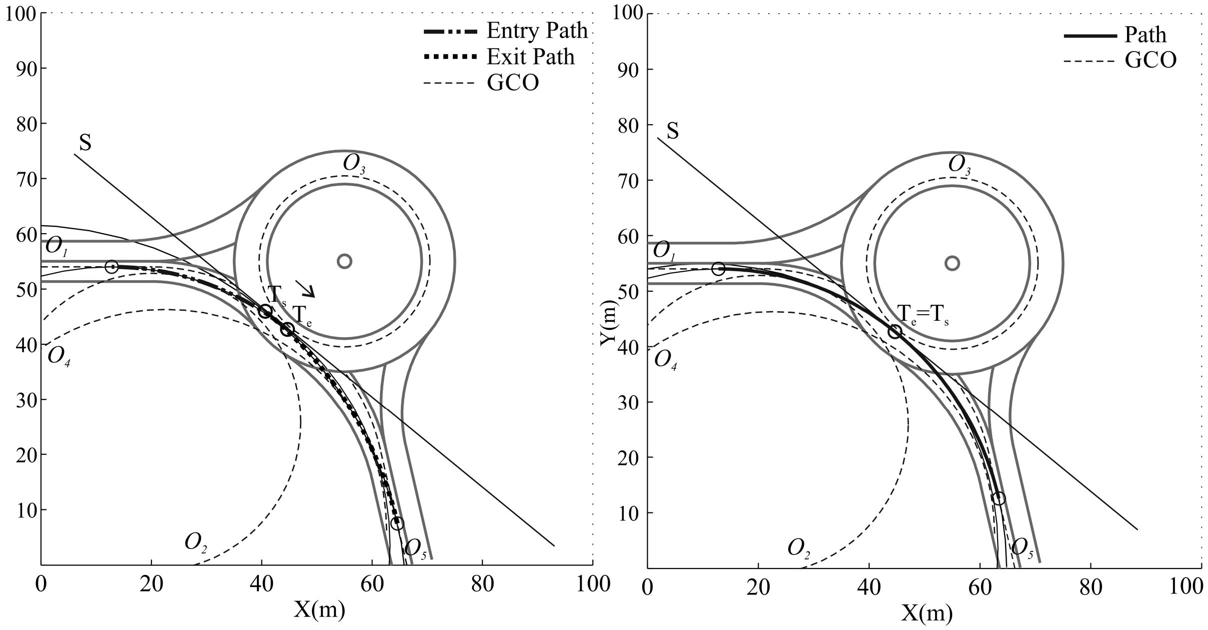
### Methodology for direct paths (MDIP)

The following steps are involved in the process of defining a direct path between an entry and an exit (Fig. 4):

- Plot a line *S* passing through points $P_e$ and $P_s$.
- If line *S* crosses $O_3$, a direct path is not possible (or infeasible) and the procedure is stopped. Otherwise, the procedure is continued.
- Plot the entry path as a circular arc tangent to $O_1$, $O_2$, and *S*. The tangent point on line *S* is $T_e$.
- Plot the exit path as a circular arc tangent to $O_4$, $O_5$, and *S*. The tangent point on line *S* is $T_s$.
- If the entry and exit paths intersect, the exit path must be rebuilt as a circular arc tangent to $O_5$ and *S* and passing through $T_e$. A layout of this step is shown in Fig. 5. $T_e$ and $T_s$ are located at the same place.



**[Fig. 4 Approximately here]**



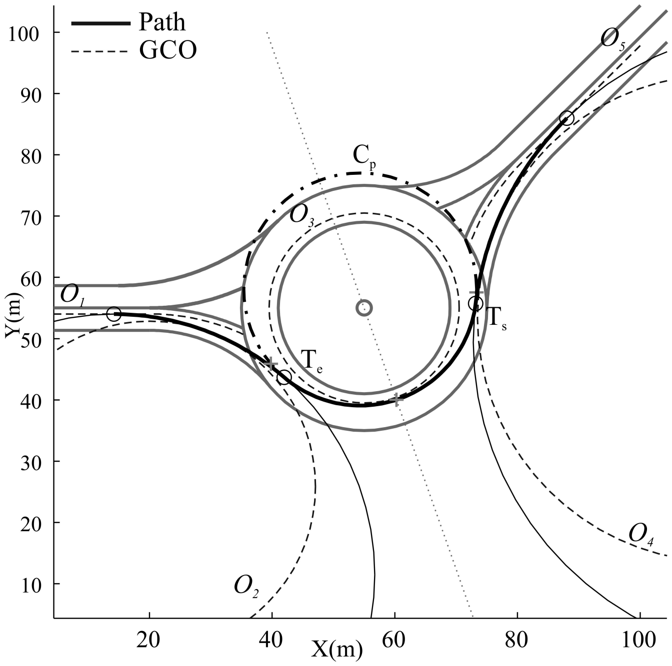
**[Fig. 5 Approximately here]**

### Methodology for deflected paths (MDEP)

A deflected path between an entry and an exit is obtained using points $P_e$, $P_c$, and $P_s$ as follows (Fig. 6):

- Plot a circular arc $C_p$ passing through points $P_e$, $P_c$, and $P_s$.
- Plot the entry path as a circular arc tangent to $O_1$, $O_2$, and $C_p$.
- Plot the exit path as a circular arc tangent to $O_4$, $O_5$, and $C_p$.

When the length of the circulatory path segment is less than a predefined minimum value, the obtained solution is considered infeasible.



**[Fig. 6 Approximately here]**

## Methodology for searching the fastest paths

In this section, a methodology is proposed to search for the fastest vehicle path between a specific entry and exit based on the generation of a group of feasible paths and the selection of the fastest.

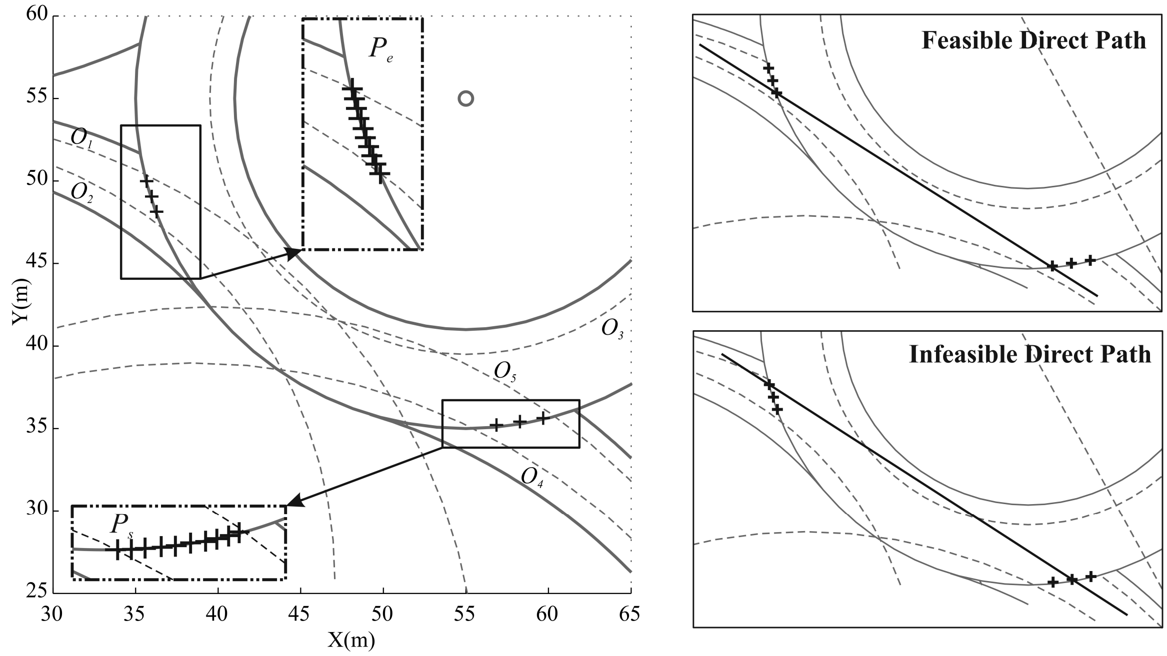
### *Step 1: Data entry*

The input data of the problem are the geometry of the roundabout and the GCO for the specific entry and exit. GCO is defined from the geometry of the roundabout.

### *Step 2: Computation of feasible direct paths*

First, two sets of points $P_{e,i}$ and $P_{s,j}$ (i, j=1,2,…, N) are generated at the entry and exit, which are then placed on the inscribed circle, uniformly distributed along the section between the points of intersection with elements $O_1$ and $O_2$ in case of $P_e$ and with elements $O_4$ and $O_5$ in case of $P_s$ (Fig. 7). For practical applications, ten-point sets (N=10) generally yield sufficient precision while avoiding a high computational load. This recommendation is based on the results of several trial applications of the method to roundabouts with an inscribed circle diameter of 30 m, 35 m and 40 m, and with different arrangements of the approach legs. For each combination of the inscribed circle and of the arrangement of the approach legs, the fastest vehicle paths were computed using different values of N (N= 2, 3, …, 40), and the radii of the paths were compared. It was found that from a value of N=10 the variation of the radii of the paths was less than 5%, but for N<10 the variations were in most cases greater than 5%.

For each possible combination of points $P_{e,i}$ and $P_{s,j}$ a path is computed using the MDIP. $N^2$ paths are tried, where some of them can be feasible and others infeasible. If no feasible path is found, the movement is considered to be deflected and the procedure continues at Step 3. Otherwise, the movement is considered to be direct and the procedure continues at Step 4.



**[Fig. 7 Approximately here]**

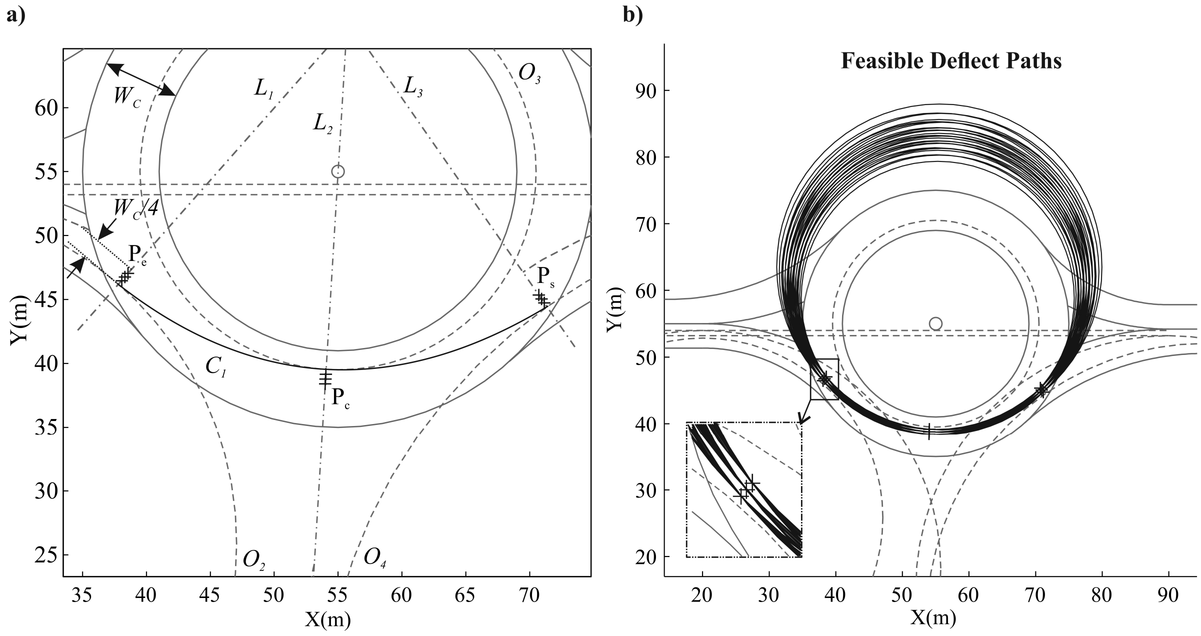
### ***Step 3: Computation of feasible deflected paths***

In this case, three sets of points $P_{e,i}$, $P_{c,k}$, and $P_{s,j}$ (i, k, j=1,2,…,M) are generated and placed as follows (Fig. 8):

- Plot a circumference $C_1$ tangent to $O_2$, $O_3$, and $O_4$. The tangent points will be located at the entry, at the circulatory roadway, and at the exit.

- Next, three lines $L_1$, $L_2$, and $L_3$ are plotted from the center of $C_1$ to the tangent points. The sets of points $P_{e,i}$, $P_{c,k}$, and $P_{s,j}$ are placed on the lines $L_1$, $L_2$, and $L_3$, respectively (Fig. 8). The points of each set are uniformly distributed along a section beginning in the tangent point and finishing at a distance equal to a quarter of the circulatory roadway width. In this case, three-point sets are generally sufficient for precise computation of deflected paths. To obtain this value, experimental tests similar to those performed for direct paths were made.

Finally, for each possible combination of points $P_{e,i}$, $P_{c,k}$, and $P_{s,j}$, a path is tried using the MDEF. A maximum number of $M^3$ feasible paths are then obtained.



**[Fig. 8 Approximately here]**

***Step 4: Selection of the path***

In this step, the fastest path among the set of feasible trajectories is selected on the basis of an estimation of the travel time required by a vehicle to run the path. To that end, the speed at each circular arc may be estimated using the relationship between speed and horizontal curvature proposed by Rodegerdts et al. (2007), unless an alternative relationship calibrated for local conditions is available.

A threshold speed equal to the design speed of the approach roads is imposed. Finally, the corresponding travel time at each path is obtained from the speed and length of the arcs, and the path having the minimum travel time is selected as the fastest vehicle path.

## CASE STUDY

In this section, an example of the application of the developed methodology is presented. A single-lane three-leg roundabout was selected in which all the possible types of trajectories described above exist to illustrate the efficiency of the procedure in defining the fastest paths. The evaluation has been performed following the recommendation of US and Spanish guidelines which do not consider the computation of the fastest vehicle paths corresponding to U-turns. However, their computation is possible using the proposed methodology. The applicability of the resulting paths to assess the consistency of the design was also demonstrated.

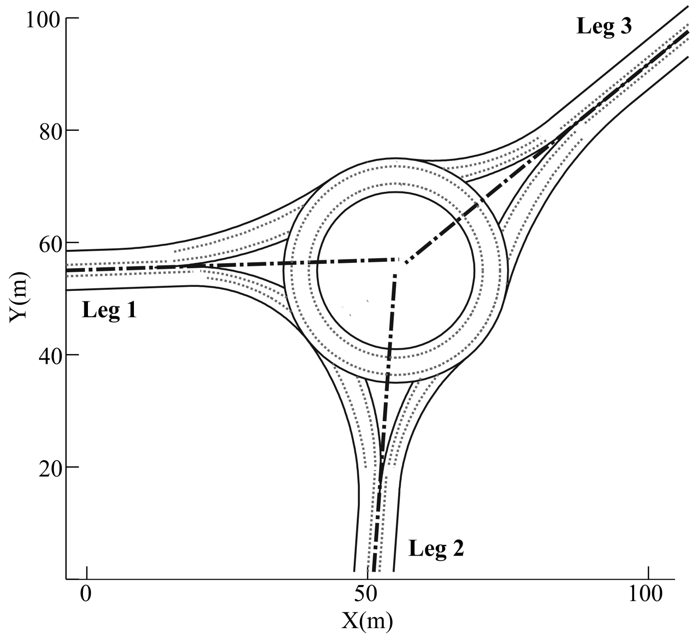
### Input data

Table 1 contains the data used for defining the geometry of a three-leg roundabout with a roadway approach width of 7 m. The corresponding drawing is shown in Fig. 9. The constraints in the path definition were obtained from the following data: $d_1 = 1$ m, $d_2 = 1.5$ m, $d_3 = 1.5$ m, $d_4 = 1.5$ m, and $d_5 = 1$ m. In case of deflected paths, a minimum length of the circulatory path segment of 20 m was adopted to consider a solution feasible. The design speed of the approaches was 80 km/h.

**[Table 1 Approximately here]**

**Table 1.** Values of the Variables that Define the Roundabout Geometry

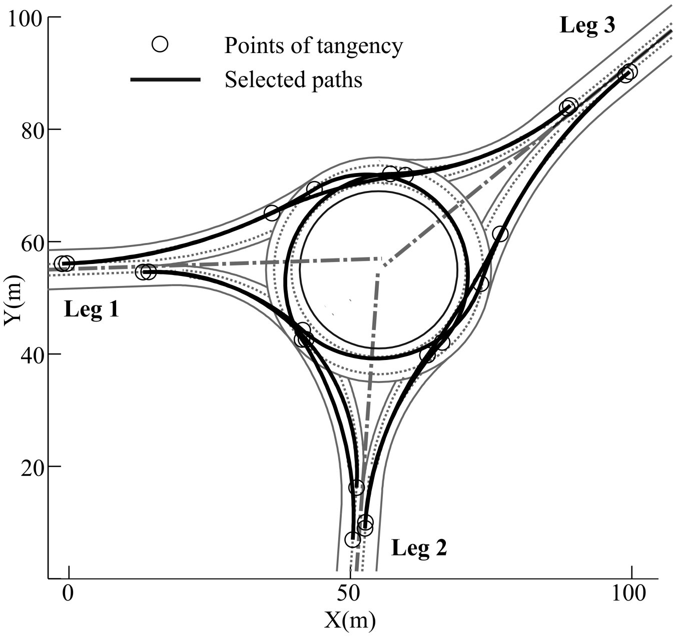
| | LE (m) | WE (m) | LS (m) | WS (m) | Xc (m) | Yc (m) | DIC (m) | Wc (m) |
|---|---|---|---|---|---|---|---|---|
| Leg | Entry splitter island length | Entry width | Exit splitter island length | Exit width | Roundabout center coordinate X | Roundabout center coordinate Y | Diameter of the inscribed circle | Circulatory roadway width |
| Leg 1 | 18 | 4.3 | 23 | 5.5 | 55 | 55 | 40 | 6 |
| Leg 2 | 21 | 4.3 | 18 | 5.5 | | | | |
| Leg 3 | 20 | 4.3 | 25 | 5.5 | | | | |



**[Fig. 9 Approximately here]**

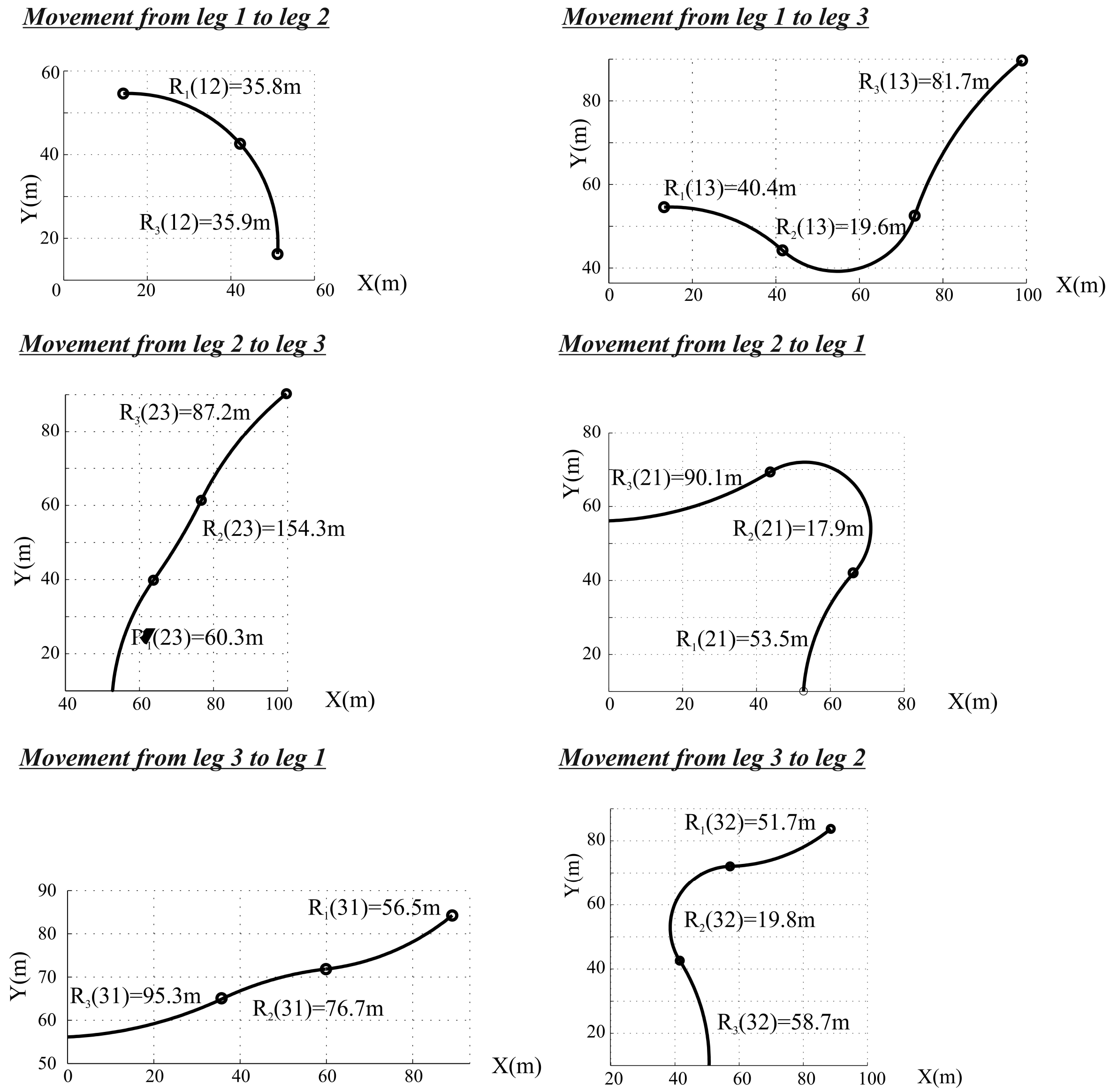
### Computation of the fastest paths

The results of the application of the proposed methodology are shown in Fig. 10. The thicker black lines represent the selected paths between each entry and exit, and the circles represent the points of tangency on the paths. A drawing with the geometric details of the selected paths is shown on Fig. 11. For a deflected path, $R_1$ is the entry radius, $R_2$ is the circulatory roadway radius, and $R_3$ is the exit radius. A direct path comprises circular curves at the entry and exit, linked by an intermediate tangent that may be reduced to a point. $R_2$ is $\infty$ in the first case, and it does not exist in the second.



383

384 **[Fig. 10 Approximately here]**



*Movement from leg 1 to leg 2*

*Movement from leg 1 to leg 3*

*Movement from leg 2 to leg 3*

*Movement from leg 2 to leg 1*

*Movement from leg 3 to leg 1*

*Movement from leg 3 to leg 2*

**[Fig. 11 Approximately here]**

**Design evaluation**

At this stage, the resulting paths are used to assess the consistency of the design. Therefore, speeds along the paths are computed and subsequently used to evaluate speed consistency. Table 2 shows the speeds obtained at the arcs of each path using the speed–radius relationship given in Equation (1). $V_1$, $V_2$, and $V_3$ are the speeds corresponding to $R_1$, $R_2$, and $R_3$, respectively. The origin and destination legs are shown in parentheses.

**[Table 2 Approximately here]**

**Table 2.** Vehicle Speeds Along the Fastest Paths (km/h)

| | Path from Leg 1 to | | |
|---|---|---|---|
| Leg 2 | $V_1$ (12)= 34.9 | $V_2$ (12)= - | $V_3$ (12)= 34.9 |
| Leg 3 | $V_1$ (13)= 36.5 | $V_2$ (13)= 25.7 | $V_3$ (13)= 48.0 |
| | Path from Leg 2 to | | |
| Leg 3 | $V_1$ (23) = 42.7 | $V_2$ (23) = 54.9 | $V_3$ (23) = 49.2 |
| Leg 1 | $V_1$ (21) = 40.7 | $V_2$ (21) = 24.9 | $V_3$ (21) = 49.8 |
| | Path from Leg 3 to | | |
| Leg 1 | $V_1$ (31) = 41.6 | $V_2$ (31) = 42.4 | $V_3$ (31) = 50.9 |
| Leg 2 | $V_1$ (32) = 40.2 | $V_2$ (32) = 25.8 | $V_3$ (32) = 42.2 |

To achieve a good speed consistency of the design, relative speeds between conflicting traffic streams and between consecutive geometric elements should be minimized. Table 3 shows the results obtained for this case study.

**[Table 3 Approximately here]**

**Table 3.** Speed Consistency Analysis

| Relative speeds between conflicting traffic stream (km/h) | | | Relative speeds between consecutive geometric elements (km/h) | | |
|---|---|---|---|---|---|
| Conflicting speed 1 | Conflicting speed 2 | Relative speed | Speed 1 | Speed 2 | Relative speed |
| $V_1$ (12) = 34.9 | $V_2$ (32) = 25.8 | 9.1 | $V_1$ (12) = 34.9 | $V_3$ (12) = 34.9 | 0.0 |
| $V_1$ (13) = 36.5 | $V_2$ (32) = 25.8 | 10.7 | $V_1$ (13) = 36.5 | $V_2$ (13) = 25.7 | 10.8 |
| $V_1$ (23) = 42.7 | $V_2$ (13) = 25.7 | 17.0 | $V_2$ (13) = 25.7 | $V_3$ (13) = 48.0 | 22.3 |
| $V_1$ (21) = 40.7 | $V_2$ (13) = 25.7 | 15.0 | $V_1$ (23) = 42.7 | $V_2$ (23) = 54.9 | 12.2 |
| $V_1$ (31) = 41.6 | $V_2$ (21) = 24.9 | 16.7 | $V_2$ (23) = 54.9 | $V_3$ (23) = 49.2 | 5.7 |
| $V_1$ (32) = 40.2 | $V_2$ (21) = 24.9 | 15.3 | $V_1$ (21) = 40.7 | $V_2$ (21) = 24.9 | 15.8 |
| | | | $V_2$ (21) = 24.9 | $V_3$ (21) = 49.8 | 24.9 |
| | | | $V_1$ (31) = 41.6 | $V_2$ (31) = 42.4 | 0.8 |
| | | | $V_2$ (31) = 42.4 | $V_3$ (31) = 50.9 | 8.5 |
| | | | $V_1$ (32) = 40.2 | $V_2$ (32) = 25.8 | 14.4 |
| | | | $V_2$ (32) = 25.8 | $V_3$ (32) = 42.2 | 16.4 |

These results indicate that the speed differential between conflicting traffic stream ranges 9.1–16.9 km/h, with a mean of 14 km/h, and that between consecutive geometric elements ranges 0.0–24.9

km/h, with a mean of 12 km/h. The geometric design meets the speed consistency criterion specified in relevant international design guidelines (Rodegerdts et al. 2010; Austroads 2015).

## CONCLUSION

This study developed a systematic procedure to identify the fastest paths for all possible movements by using the roundabout geometry and the minimum distance between the vehicle and the edge of the roundabout as input data. The following aspects of the proposed methodology are highlighted:

- It supports the speed consistency assessment of the design as prescribed by most relevant international guidelines.
- It can be easily implemented in roundabout design software.
- It provides an efficient alternative to the current practice of drawing successive trial solutions by freehand until a satisfactory one is reached. In comparison with other existing semiautomatic methods, the proposed method has the ability to solve all the relevant movements in the roundabout.
- It is applicable indistinctively to one-lane or multi-lane roundabouts, and for any arrangement of the approach legs.
- It ensures convergence to a single common solution, as it does not depend on personal judgment of the designer. Therefore, it can be easily implemented in a heuristic roundabout design procedure.
- A limitation of the method is that it has to be included in a comprehensive roundabout design software for a broad use.
- Its applicability in practice has been demonstrated in a case study.

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