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An Improved Roundabout Design Process with Computer Assisted Analysis

- Luis Ramos, Ingeniero de Caminos, Canales y Puertos, Director General, Estudios y Soluciones Informáticas de Ingeniería S.L., c/ Joaquín Mª López 10, 28015 MADRID, Spain. T +34 915 700 135 F: +34 914 250 769 www.esiisl.com, luis@esiisl.com

- Sandro Rocci, Dr. Ingeniero de Caminos, Canales y Puertos, Professor Emeritus, Universidad Politécnica de Madrid. E.T.S: Ingenieros de Caminos, Canales y Puertos, c/ Profesor Aranguren s/n, Ciudad Universitaria, 28040 MADRID, Spain. T: (+34) 619 480 972. F: (+34) 915 427 742. srocci@recol.es. **Corresponding Author**.

- Daniel Shihundu, P.Eng., MBA, MIHT, Senior Civil Engineer, Transoft Solutions, Inc., Suite 250 - 13575 Commerce Parkway, RICHMOND, BC, Canada, V6V 2L1, T : (+1) 604 244 3821, F : (+1) 604 244 1770. daniel@transoftsolutions.com

ABSTRACT

Roundabout design process has been known to be complex and iterative. It involves the balancing of cost, performance, safety and capacity related aspects. In some of the design approaches, performance and safety aspects of roundabout design rely on manual and sometimes hand-sketched evaluations for the roundabout layout and fastest path approximation. With each manual modification done on the roundabout layout due to right-of-way or other constraints, vehicle manoeuvrability issues and other safety concerns, the designer has to re-examine these effects on the roundabout geometry.

With the advancement in technology, computerized approaches have been developed to greatly reduce or eliminate the need for iterative design processes, while at the same time assisting the designer to achieve a final design more effectively. This paper identifies critical components of roundabout design, analyzes current design methods, and outlines the workflow for an improved design process using modern computer software, which harnesses their immense capabilities to carry out repetitive tasks.

Although the use of software will not automatically create a good roundabout design, it should give more time to designers to explore other options considering the operational, economic, social and environmental impacts; and to apply judgment. If properly used, it could result in better roundabout horizontal designs.

INTRODUCTION

Although there are earlier versions of intersections where all vehicles circle a central island, modern roundabouts originated in the UK towards the middle of last century; their migration across the Atlantic has been much more recent. Their operating and safety performances are deemed satisfactory in most environments.

In a modern roundabout yield control is used on all entries; the circulatory roadway has no control (1). Vehicle entrance into the roundabout is achieved through a low-speed gap acceptance process, rather than a high-speed merge:

- Entering traffic is required to yield to circulating traffic.
- Geometric constraints (path curvature and narrow pavement widths) slow entering vehicles even if there is no circulating traffic.

This paper concerns the process of roundabout design and its evolution in the later years thanks to computer applications.

GEOMETRIC DESIGN

Principles

Geometric design of modern roundabouts (2) is an iterative process (Fig. 1) in which layout is analyzed in relationship with:

- Accommodation of large vehicles.
- Operational performance.
- Safety performance.

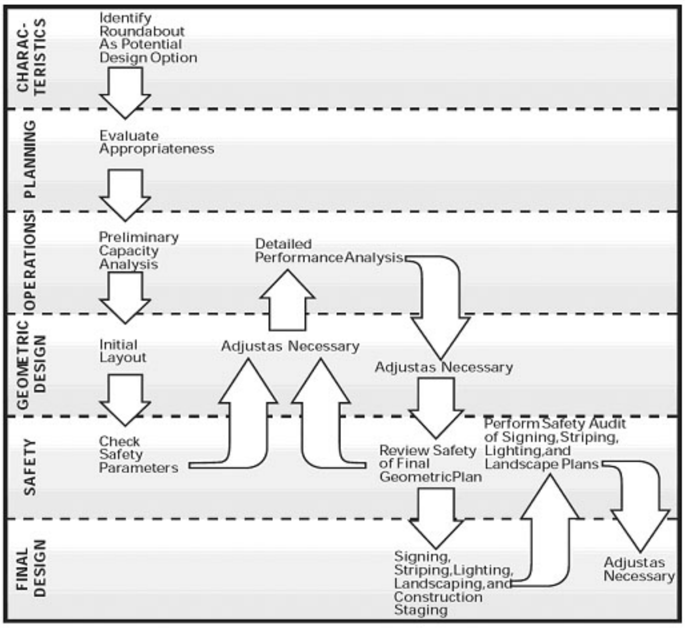

FIGURE 1 Roundabout design flowchart (2).

Even minor changes in layout can result in significant changes in the other three features. In a preliminary design stage, the following fundamental decisions must be made:

- Alignment and arrangement of the approach legs, many of which can be often modified.
- Design vehicle(s) to be accommodated, with an offset to pavement edges (or, in two-lane circulatory roadways, to other vehicles). Sometimes, a truck apron is placed next to the central island, so that the largest vehicles can pass over it.
- Number of lanes of circulatory roadway. In Spain (3), one lane can carry up to 1,200 pcph; two lanes up to 2,200 pcph; more than two lanes is not recommended although they are used.
- Inscribed circle diameter and location of its center. If roundabout is not circular, operation and safety performances decrease, mainly due to larger speed variations along the circulatory roadway.

Recommended design vehicles in Spain (3) are described in Table 1; also dimensions and minimum turning radii are given. The vehicle's maximum steering angle (lock angle) and the articulating angle (between adjoining units of a tractor-semitrailer or an articulating bus) are critical, not to be exceeded.

TABLE 1. Design vehicles for roundabouts recommended in Spain.

<table>
<tr><th colspan="3">Operating Conditions</th><th>Normal</th><th>Exceptional</th></tr>
<tr><td rowspan="3">Single-lane circulatory roadway</td><td colspan="2">Non-significant truck proportion</td><td>Van</td><td rowspan="3">Semi-trailer</td></tr>
<tr><td colspan="2">Significant truck proportion, no buses</td><td>Light single-unit truck</td></tr>
<tr><td colspan="2">Significant bus proportion</td><td>Single-unit bus</td></tr>
<tr><td rowspan="3">Two-lane circulatory roadway</td><td colspan="2">Less than 200 trucks per hour (II)</td><td>Two simultaneous passenger cars</td><td>Most unfavorable of:
- Semi-trailer
- Simultaneous passenger car + van</td></tr>
<tr><td rowspan="2">More than 200 trucks per hour</td><td>Non-significant bus proportion (III)</td><td>Simultaneous passenger car + light single-unit truck</td><td rowspan="2">Truck + trailer</td></tr>
<tr><td>Significant bus proportion (IV)</td><td>Simultaneous passenger car + single-unit bus</td></tr>
</table>

There has been an evolution in the roundabout design criteria. Earlier versions were based on experience at existing roundabouts, and consisted of a set of rules concerning ranges of values for certain dimensions and angles so that operation, safety and accommodation were acceptable. More modern criteria are based on modeling actual vehicle paths, and analyzing the swept space and the speed profile. Some of these paths are supposed to be the fastest possible, determined in a rather subjective way.

Vehicle kinematics

Vehicle path is usually defined by the center of the driving axle. In a single-unit vehicle at very low speeds the differential equation giving the position of the turning center is

$$\pm \frac{d\beta}{ds} = \frac{1}{\rho} - \frac{\sin \beta}{b} \qquad [1]$$

where: **s** is the distance traveled along the path,
β is the angle shown in Fig. 2,
ρ is the path radius of curvature,
b is the distance between axles.

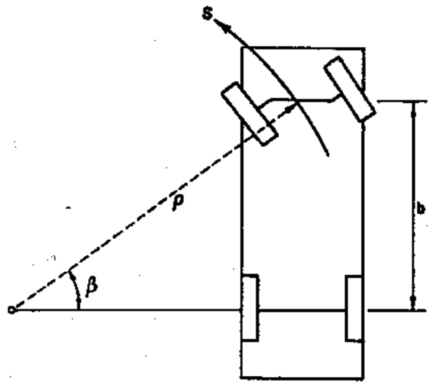

FIGURE 2 Geometry of a single-unit turning vehicle (3)**.**

Positive sign is for forward movement. Once β is known, the swept path can be easily computed. Paths of semi-trailer and other vehicle configurations are based on a similar reasoning. Equation [1] and its similes cannot be readily integrated: they pertain to curves of pursuit similar to the tractrix. But they can be integrated by finite differences: there are several computer applications which solve the problem both numerically and graphically.

Elements of the alignment of a vehicle path are tangents and circles. To provide room for turning the steering wheel between reverse curves, a short tangent is interposed, or more accurately spirals are used. Paths usually analyzed are (Fig. 3):

- Right turn, taking the first exit after the entry: one single curve.
- Through movement, taking an exit further downstream so overall path is approximately straight: two reverse curves, to cater for the entry and exit deflections.
- Left turn, taking another exit still further downstream so that the vehicle turns more than 90 degrees: two reverse curves.

Path layout depends on alignment of approach legs, and values of radii and spiral lengths. It should start and end at the appropriate approach tangents, and swept areas should leave an offset to the central island and/or outer roadway edges; in two-lane circulatory roadways, also to the swept path of other vehicles in the other lane.

To achieve the fastest path, intermediate tangent lengths on reverse curves should be zero. In Spain (3) the following additional criteria are used:

- **R_1** < **R_2** < **R_3** : easy with a single-lane circulatory roadway.

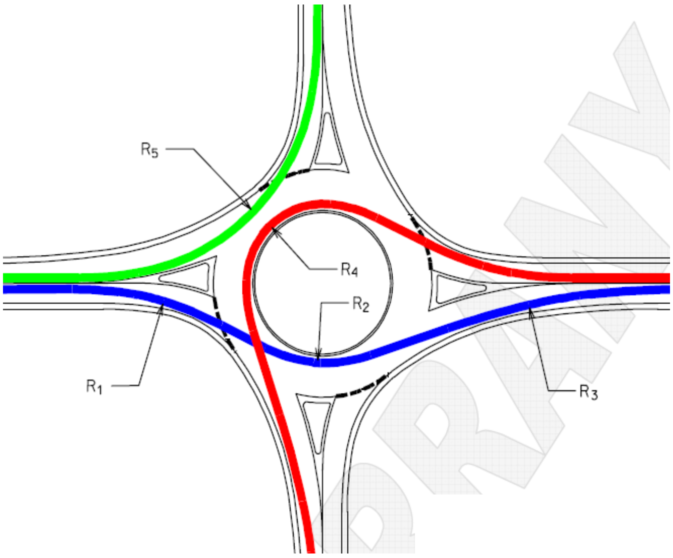

FIGURE 3 Paths in a single-lane roundabout (3)**.**

- **R_1** and **R_5** between 6 and 100 m (optimum 20 m).
- **R_3** not less than 40 m (20 m if there is a pedestrian crossing near).
- **R_2 <** 1.6 *** R_4** [2]
- For small deflection angles, circle length should be reduced to zero.
- For large deflection angles, each spiral should account for 20 percent of total angle.
- For intermediate angles, minimum spiral length corresponds to an offset of **ΔR** = .5 m to the tangent; and maximum length, to 1.5 times the minimum.
- To allow the steering wheel to be turned at a uniform speed in reverse curves, both connecting spirals should have the same parameter (product of radius and distance to the point of zero curvature).

Vehicle dynamics

Although the kinematic model normally gives a good approximation, at somewhat higher speeds, side friction between tires and pavement play a larger role, and offtracking can be slightly different (4).

Maximum side friction should not exceed a limit (3)

$$f_t = \frac{1}{1.29 + \frac{V_{85}}{11.4}} \quad [3]$$

where: f_t is the limit associated with comfort at the design speed.
V_{85} (km/h) is the 85th percentile speed.

With side friction, curvature and superelevation, a speed profile can be obtained for any vehicle path. Pertaining criteria established in Spain (3) are shown in Table 2.

TABLE 2. Criteria for speed profiles in roundabouts.

Radii	Environment		Criteria
R_3	Urban		V_3 < 45 km/h or alternatively, V_2 < 30 km/h
R_1 and R_2	Urban	Single-lane	$V_1 < V_2$ + 20 km/h
		Two-lane	$V_1 < V_2$ + 20 km/h and $V_1 > V_2$ - 10 km/h
	Rural	Single-lane	$V_1 < V_2$ + 15 km/h
		Two-lane	$V_1 < V_2$ + 15 km/h and $V_1 > V_2$ - 10 km/h
R_3 and R_2	Urban		$V_3 > V_2$ - 5 km/h
	Rural		$V_3 > V_2$
R_1 and R_4	Any		$V_1 < V_4$ + 30 km/h
R_5 and R_4	Any		$V_5 < V_4$ + 20 km/h
R_2 and R_4	Any		$V_2 < V_4$ + 20 km/h

MANUAL APPROACH

Current roundabout design practice involves two broad approaches: manual and computerized. The manual approach requires the use of hand-drawn sketches and pure CAD tools (AutoCAD, Microstation etc.) which have no inbuilt roundabout design parameters. In many cases, to complete a roundabout design proficiency in the use of CAD drafting tools is necessary, since it may involve drawing vehicle paths by freehand on a preliminary layout of the roundabout and then checking their consistency. Thus, the onus rests with the designer to make sure that the roundabout layout and design are safe, cost-effective and operational. The computerized approach is discussed in more detail later.

Left turn

The middle radius R_4 is readily determined, since the circle is concentrical to the central island. In the aforementioned Spanish document (3), width of circulatory roadway (plus eventual truck apron) is given in Table 3.

TABLE 3. Width of circulatory roadway (including truck apron) recommended in Spain.

Outer diameter (m) **of roundabout**	**Single-lane width** (m)	**Two-lane width** (m)		
		II	**III**	**IV**
28	8.0	8.0	9.6	12.6
32	7.2	7.7	9.1	11.1
36	6.7	7.5	8.7	10.4
40	6.3	7.4	8.5	9.9
44	6.0	7.3	8.3	9.5
48	5.8	7.2	8.1	9.2
52	5.6	7.1	8.0	9.0
56	5.4	7.0	7.9	8.8
60	5.3	7.0	7.8	8.6

II, III and IV refer to situations in Table 1.

The other two radii are chosen so that the swept path leaves an offset to the outer roadway edges: the larger the radius, the fastest the path.

Right turn

Using Table 2 an upper limit to can be determined from $\mathbf{R_4}$. This means that layout must be such, that no larger $\mathbf{R_5}$ is possible.

The other two radii are chosen so that the swept path leaves an offset to the outer roadway edges: the larger the radius, the faster the path.

Through movement

This is the trickiest case for determining the fastest path.

- Using equation [2] and Table 2, an upper limit to $\mathbf{R_2}$ can be determined from $\mathbf{R_4}$. This means that layout must be such, that no larger $\mathbf{R_2}$ is possible.
- An upper limit to $\mathbf{R_1}$ can be determined both from $\mathbf{R_4}$ and the chosen $\mathbf{R_2}$; in two-lane circulatory roadways, a lower limit from the chosen $\mathbf{R_2}$. This means that layout must be such, that no larger or smaller $\mathbf{R_1}$ is possible.
- An upper limit for can be determined from Table 2, and a lower limit from the chosen $\mathbf{R_2}$. This means that layout must be such, that no larger or smaller $\mathbf{R_3}$ is possible. Also, $\mathbf{R_3}$ should not be less than 40 (20) m.

For a given roundabout approach design, several trials must be made to find the combination of **R1**, $\mathbf{R_2}$ and $\mathbf{R_3}$ fulfilling all the rules and achieving the fastest path.

Speed profile

Rules for setting up speed profiles from the layout are simple:

- In a circle of radius **R** (m) and superelevation e (%), transverse friction factor f given by Eq. [4] should not exceed the limit given by Eq. [3]; speed **V** (km/h) can be considered as constant.

$$f = \frac{V^2}{127 \cdot R} - \frac{e}{100} \qquad [4]$$

- In spirals and tangents, deceleration or acceleration rate is constant, but limited.

Fastest path between two given points corresponds to minimum travel time between them, i.e. to a minimum value of the integral of the inverse of the speed profile.

Limitations of manual approaches

Roundabout designs are carried out by designers who possess varying levels of experience and expertise. While for a very experienced designer it may be easy to complete the design in a relatively short time, to others freehand sketches and CAD drafting tools do not provide the immediate feedback on key parameters as the design progresses, making it both complex and iterative. Manual methods usually require dealing with one particular design aspect at a time. Roundabout accommodation, operational and safety issues are not readily apparent with each layout modification; these issues have to re-examined again and again.

COMPUTERIZED APPROACH

Principles

With the advent of computers, efficiency to perform certain tedious, laborious and repetitive tasks has been improved. Their computing power and speed have increased, prompting the software industry to create more specialized and complex applications, which attempt to automate certain design processes. However, they require the computer operator to have an adequate knowledge of the design process.

Commercial applications specializing in roundabout geometry have been on the market for some time. They allow a designer to input key roundabout parameters (such as ICD), and they output a graphical representation of the roundabout. These applications are specifically written to automate the generation of any roundabout geometry; and they are based on geometrical rules, governed by ranges of values for certain dimensions and angles.

Applications use one of two types of system: a template system (AKG Software Consulting, Bentley Systems and Autodesk), or a dynamic feedback system (Transoft Solutions) which is vastly different from the other.

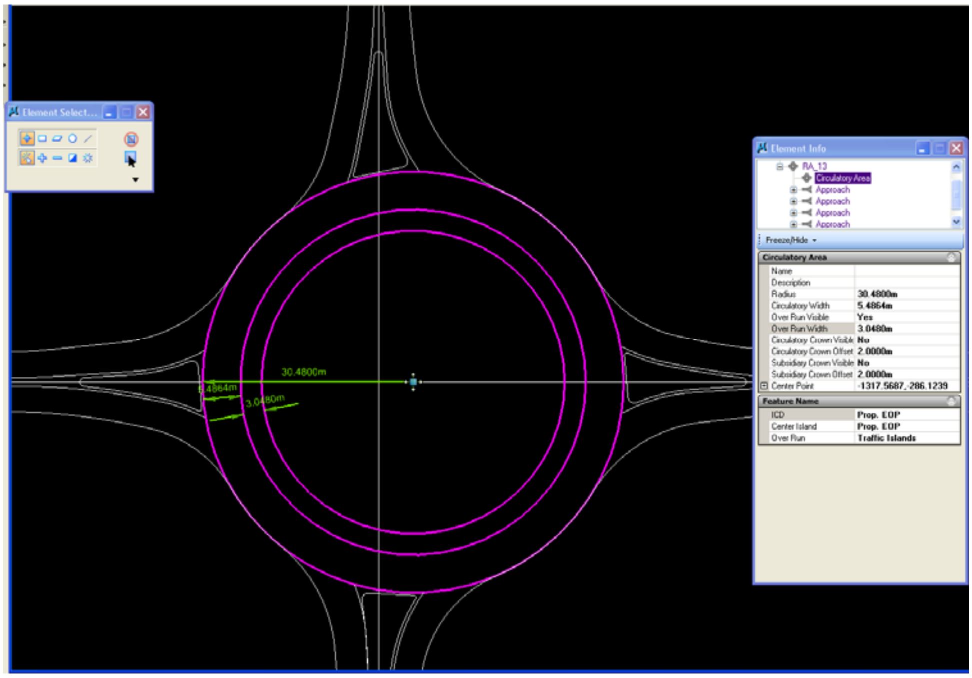

FIGURE 4 Sample Roundabout Input Data - Bentley Systems.

TORUS

Origin and Field Tests

As a spin-off of their successful vehicle swept path software (5) for analyzing intersections, a first version of TORUS was developed by Transoft Solutions, and integrates vehicle swept paths and speeds with the geometric layout.

The software's algorithms were derived from a GPS field study on vehicle paths and speed profiles, conducted in collaboration with the University of Bundeswehr in Munich, Germany. The main objective of the study (6) was to examine the driving speeds and natural path patterns, related to acceleration, deceleration and vehicle positioning (Fig. 5) for approximately 300 runs through 9 different roundabout configurations. To accurately survey the drive paths, Leica GPS 1200 Series receivers were mounted on the top of each vehicle, recording data points at every .1 second to derive the location of the vehicle body as well as the front and rear axles. Analysis and findings from this study is not the subject of this paper. Samples shown below are for information purposes only.

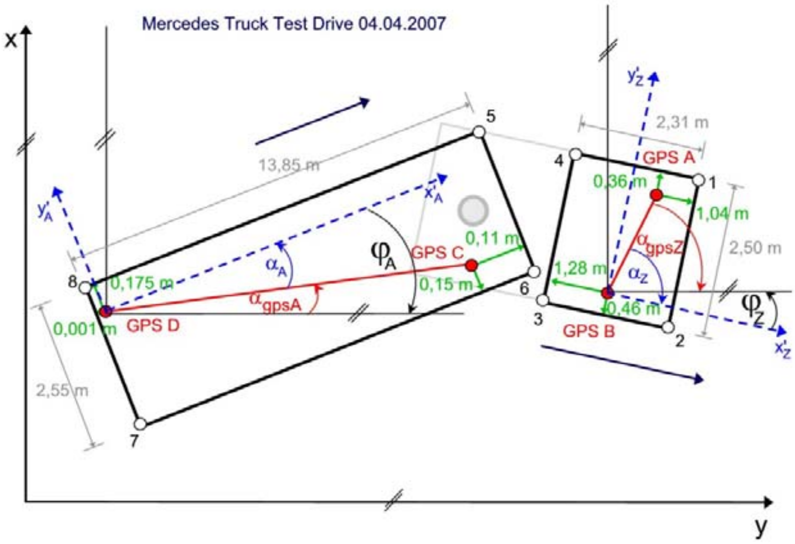

FIGURE 5 GPS Receivers located on the Semitrailer.

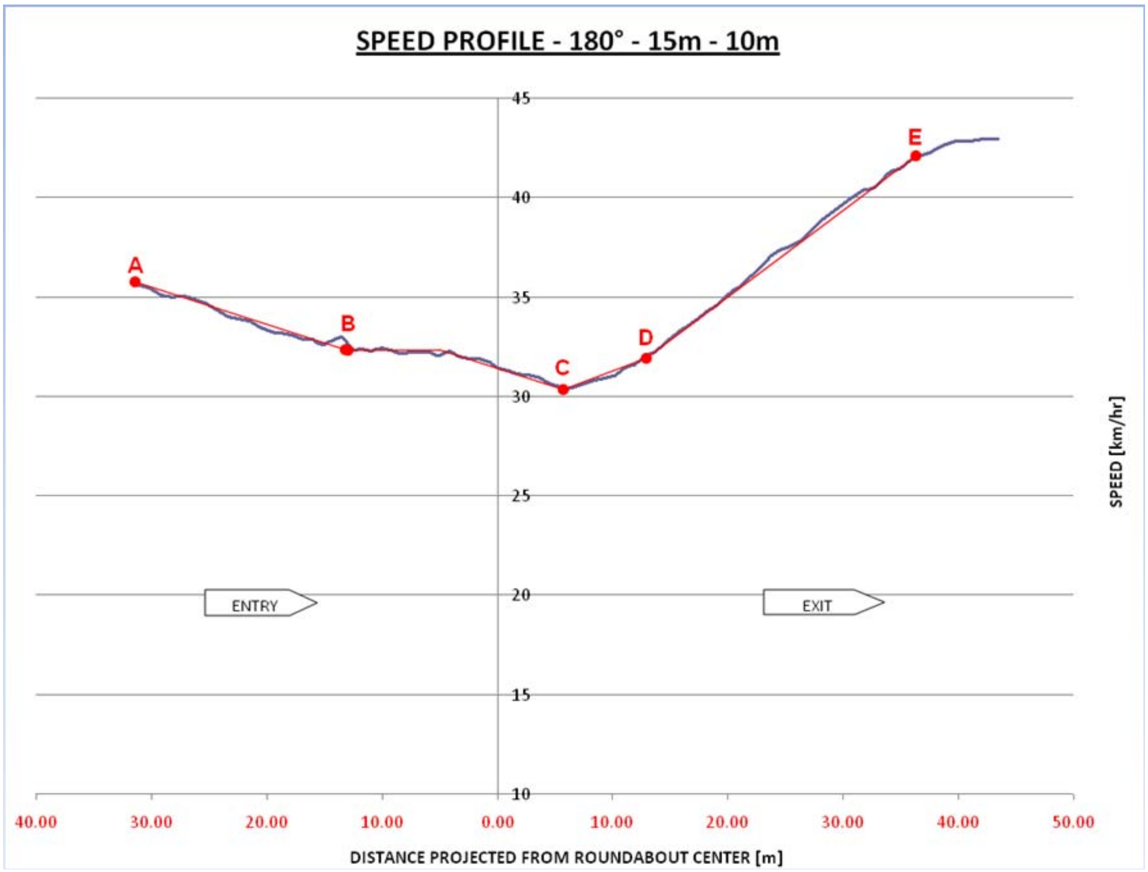

FIGURE 6 Speed Profile of a test run from the GPS Field Test (6)**.**

Management of design process allows:

- Dynamic approximations of ICD location and size.
- Drag-and-release modifications to a given path.
- Saving, recalling and comparing multiple design iterations within a single drawing to document the complete design process.
- Selecting and editing a previously generated design when evaluating alternative roundabout locations, approach alignments and associated deflection.
- Reducing the number of design iterations required to optimize layout without compromising the operational and safety performances.
- Evaluation of sightlines.

Design Guidelines

The program incorporates a set of tables stored in a database system which is also referred to as the design guidelines. Their setting is typically the first task a designer would undertake prior to laying out the roundabout geometry. Key parameters, which include the design vehicle and initial sizing of the ICD, are estimated. To determine the central island's optimal size and position, the program computes its diameter, and the width of the truck apron width if applicable.

Firstly, the parameters in the design guideline are defined, and reference lines or arcs are drawn indicating the general direction and orientation of the approach legs. The footprint of the roundabout, based on the minimum required space for the design vehicle(s) to maneuver, is automatically displayed. The design vehicle(s) are assumed to travel on pre-determined, idealized paths composed of a series of curves. Offsets from the swept paths provide an initial approximation of the roundabout layout (Fig. 5). Through internal computations and iterations, the program first determines the largest back-to-back values for $\mathbf{R_1}$, $\mathbf{R_2}$ and $\mathbf{R_3}$ which satisfy the required offsets at the median, central island and curbs; in the next step, it fits spirals between the back-to-back arcs, making the path as straight as possible, which typically represents a realistic drive pattern as noted during the field research.

In order to adjust the size of the ICD, the circulatory offsets (external and internal circulatory and lane) can be viewed and edited.

Approach Alignment

In determining the optimal alignment and arrangement of approach legs, the entry path radius and offsets for the approach leg can be modified. To provide feedback to the designer on the orientation of the approach legs, the program employs two methods for deriving the entry angle (a parameter used in several rules): to select an appropriate method, sound engineering judgment is required.

Fastest Paths and Speed Consistency

The fastest paths and speeds are computed at the same time as the geometric parameters of the roundabout (e.g. moving the roundabout centre, varying the deflection of the arms, increasing the inscribed circle diameter) are modified (Fig. 7).

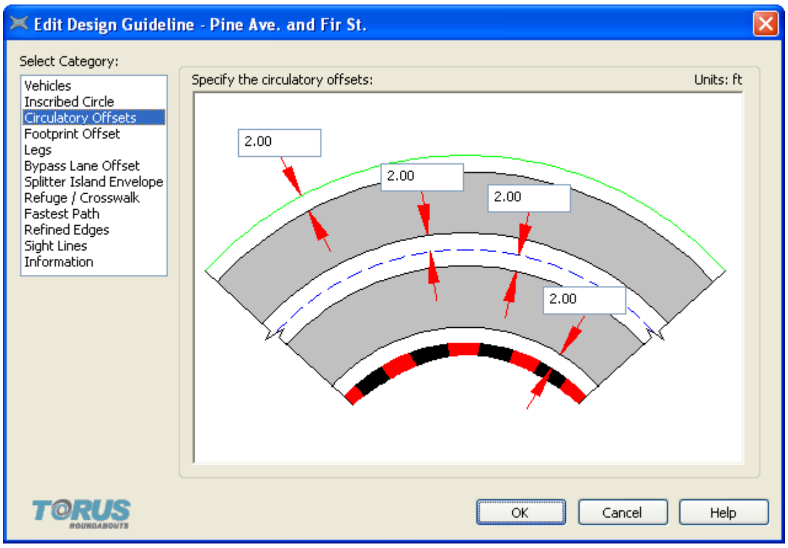

FIGURE 7 Vehicle offsets

The program uses cubic Bézier splines to model the transition spiral from tangent to circle or vice-versa, which replicates the effect of applying a rate of steer based on the vehicle's maximum steering angle, and the driver's "lock-to-lock" time.

To compute the fastest through path (a combination of $\mathbf{R_1}$, $\mathbf{R_2}$, and $\mathbf{R_3}$) and the fastest turn paths ($\mathbf{R_4}$ and $\mathbf{R_5}$), the minimum median, edge, and central island critical offsets are used as constraints. The $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$, $\mathbf{V_4}$, and $\mathbf{V_5}$ speeds are computed using Eq. [4] and a transverse friction factor similar to the one given by Eq.[3].

Moreover, the program computes the exit speed ($\mathbf{V_{3a}}$) at the exit crosswalk location bu applying Newton's formula to the circulating speed $\mathbf{V_2}$, acceleration rate, and path distance from the central island critical offset to the location of the crosswalk.

A speed consistency check is performed for each approach leg based on the following criteria:

- $\mathbf{V_1} < \mathbf{V_2} + L$
- $\mathbf{V_3} > \mathbf{V_1}$ and $\mathbf{V_3} > \mathbf{V_2}$
- $\mathbf{V_5} < \mathbf{V_1}$ and $|\mathbf{V_5} - \mathbf{V_4}| < L$

where L is the limit of the speed difference: something similar to Table 2.

Sight Line Analysis

Sight line analysis is important for determining safety constraints in a roundabout. The program checks and dynamically calculates the minimum stopping sight distance on approach, forward visibility at entry, visibility to the right, circulatory visibility and pedestrian crossing visibility. The following values of parameters are assumed by default:

- Perception-brake reaction time: 2.5 s
- Deceleration rate: 3.4 m/s^2.

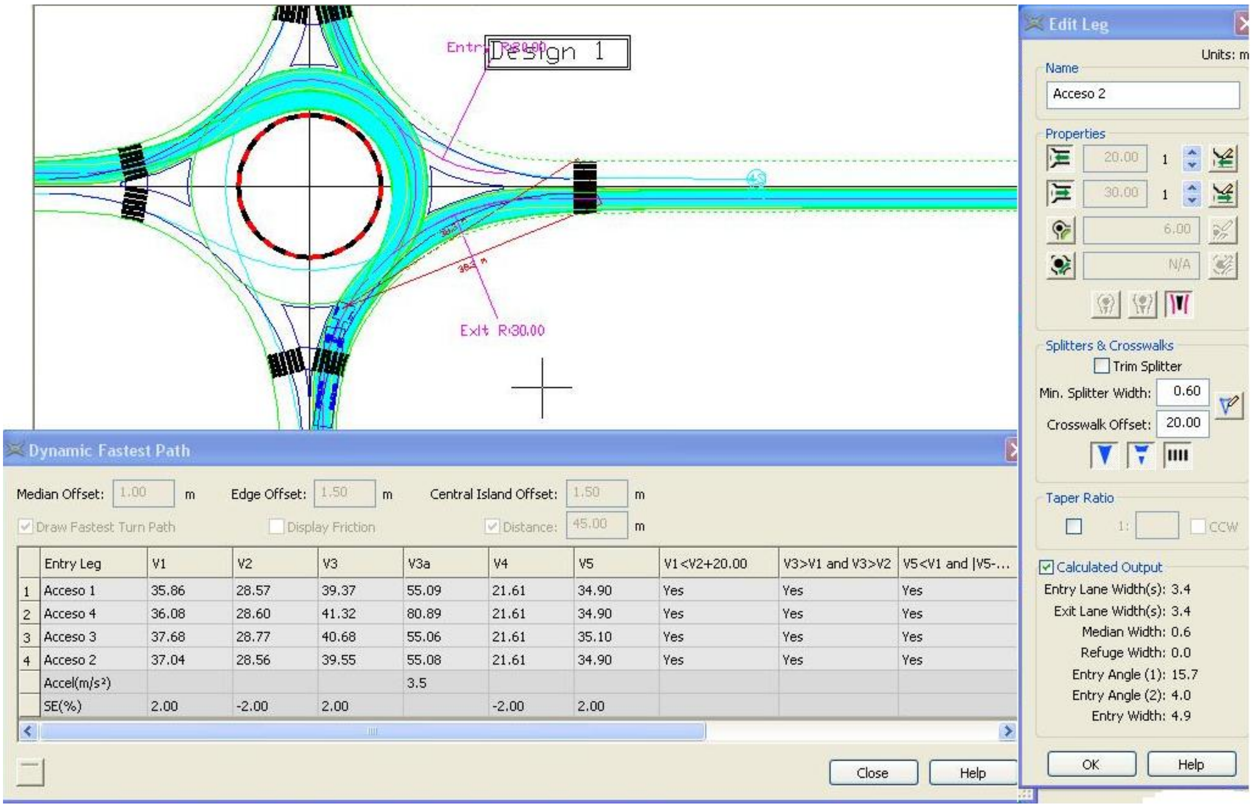

FIGURE 8 Vehicle accommodation for through and turn fastest paths

For intersection sight distance (to enable the driver, when entering the roundabout, to see the upstream entering and circulating traffic), the critical gap is assumed by default to be 6.5 s. These default values can be modified by the user at any stage of the design.

Reports

The program incorporates a Design Manager suite, enabling designers to manage multiple concepts with saving, recalling, comparing and reporting functions (Fig. 9). It also allows the similarities and differences in two design iterations to be identified.

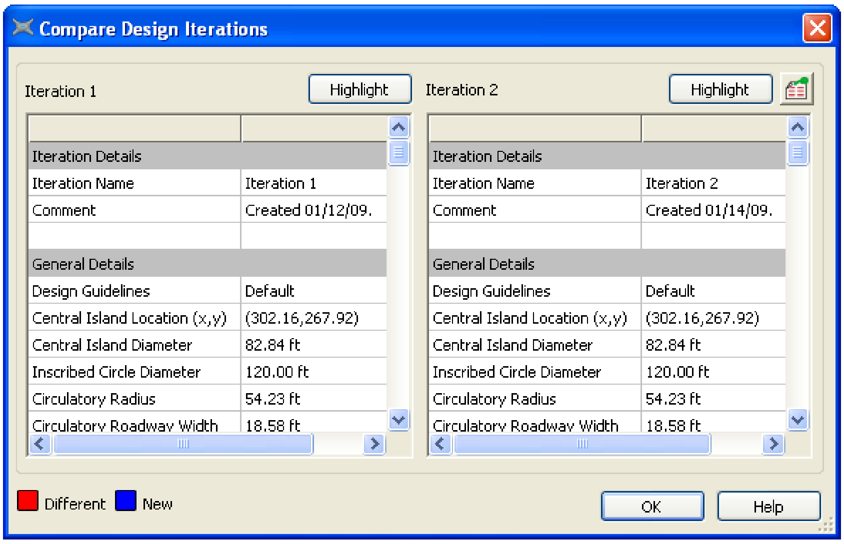

FIGURE 9 Iteration design report

Edge and Arc Refining

When a design is almost complete and an approximation of the geometric elements typically representing curbs or painted lines is required, the software automatically draws lines and arcs based on the locations of the roundabout edges, which can be fine-tuned to more closely represent final edges. Refinement is achieved through a set of three arc elements which are tangential to the selected segment ends and to each other at connections.

Limitations

Being the first version of this software, TORUS will not handle:

1. Complex scenarios
2. Vertical alignment of the roundabout, This affects the sightlines and speed
3. Roundabouts which are irregular in shapes
4. Lane usage (bike lanes etc..), lane markings, lighting etc.: things which even designing manually do not get any advantage.
5. Reference lines and arc (only to define leg orientation)
6. Weaving within the roundabout
7. Splitter island envelopes

CONCLUSIONS

This paper is aimed at highlighting certain improvements in roundabout design workflow which can be attained by the use of commercially available computerized methods which may help a designer obtain constant feedback during the design process.

Guidelines for the design of roundabouts include some recommendations (such as those in Table 2) on speed consistency for the through and turn paths, and for the accommodated design vehicle(s). Since the guidelines also give some values for radii, widths, diameters, circulatory lane(s), splitters, etc., designers could be misled into thinking that, by using these values, speed consistency and the accommodation of the design vehicle is automatically achieved. Since in many cases this is not true, a tool is needed to help check speed consistency for the fastest path, and vehicle space requirements.

Although this can be achieved through manual methods, at least theoretically, the process is laborious and calls for a great deal of effort and time on the part of the designer. Due to these drawbacks, great interest has been shown in modern computerized methods, available in software such as TORUS. Through their dynamic editing functionality and feedback, a designer can easily and quickly ascertain how a change in roundabout layout affects speed consistency for the fastest path, and the design vehicle manoeuvrability.

The use of software will not automatically create a good roundabout design; but it can give more time to designers to consider options and to apply judgment. However, it has to be ensured that whoever has the responsibility of using computer applications (including basic CAD) is thoroughly aware of what can be realistically achieved, and how. If properly used, software could result in better roundabout horizontal designs; for now, vertical alignment has not been integrated in the software.

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