Modern Roundabouts Design Study for Heavy Trucks: Argentina's case.

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ABSTRACT

Modern roundabouts adoption has strongly increased since change of give-way to circulating traffic. From that moment onwards, the most recognized Roundabout Design Guidelines have evolved throughout the implementation of numerous studies.

This paper presents the case of Argentina, as an example of a Latin American country, where Geometric Design Guidelines are not up to date. During the last decade, a considerable amount of these intersections have been built in rural surroundings and as a consequence, deficiencies in the performance become evident, especially where heavy vehicles circulation is present.

The main goal of this work is to provide recommendations on modern roundabouts geometric parameters, such as appropriate turning radius and swept path widths, and help professionals create more efficient and safer designs when heavy and articulated vehicles are involved. This paper shows the modeling process in heavy trucks circulation scenarios, using minimum turning radius templates and simulating different maneuver speeds.

The paper also exposes the downgrade of Argentinean design vehicle standards in relationship with local Transit Law, resulting in roundabout designs that consider less demanding vehicles than those actually circulating.

As a conclusion, measurements are presented in the form of tables, to help determine entry, circulatory roadway and exit widths, need for apron and its recommended width.

Keywords: Modern Roundabout, Design vehicle, Swept path width, Entry width, Circulatory roadway width, Exit width, Turning radius, Speed consistency.

INTRODUCTION

Modern roundabouts were developed in Britain in 1966, when the right of way to the circulating traffic was officially adopted. Thereafter, the design of large traffic circles, were replaced with smaller diameters, where drivers are supposed to recognize a gap in the circulating traffic to merge in. These new concepts were included in 1971 by the British Ministry of Transportation and revised in subsequent Guides in 1975, 1985 and 1993. These guidelines were "exported" to Australia and France in the 70's, and reached a larger number of countries in the 80's. In 2000, the Federal Highway Administration in the United States, added these concepts to the national roundabout design guide (1). In 2010, the second edition was published (2).

Few countries in Latin America have up-to-date Geometric Design Guides. For example, Argentinean Geometric Design Standards date from 1967, to be later slightly updated in 1980 (4). In these, what we commonly recognize as roundabouts are actually referred to traffic circles. They are basically a Spanish translation from the ASHTO Policy on Geometric Design of Rural Highways from 1965 (3). At that time, the right of way to the incoming traffic turned these circles into weaving sections, where vehicles where constantly entering the intersection, and therefore contributing to its self-saturation. The only way to increase capacity was to adopt larger diameters and distances between consecutive entries. In the rural surroundings, numerous intersections were designed under these concepts, and even today exist with their original geometry.

In recent years, however, modern roundabouts have earned a privileged place in the design of at-grade intersections in rural areas. They have been widely disseminated, to be used as appeasers in revenues to cities or at the end of diamond interchanges. These roundabouts have substantial truck traffic and, in many cases, have shown a poor performance for this type of vehicles.

Very few references to modern roundabouts design involving heavy and articulated vehicles exist in design bibliography. General publications suggest analyzing circulating paths for passenger vehicles, while in the case of heavy vehicles, the inclusion of a mountable apron (extra paved width) is recommended.

This paper is divided in three sections. In the first section, the downgrade of the Argentinean Standards in terms of design vehicles is exposed, demonstrating the existing differences between design vehicles and transit law allowed dimensions. As a consequence, designs are made for less demanding vehicles than those actually circulating.

The second section focuses on determining geometric design parameters that will streamline the design process of modern roundabouts over which heavy vehicles drive along. For this purpose, circulation paths are modeled using a software design application, different speeds scenarios and recommended geometrical parameters are tested.

Finally, previous section outcomes are presented alongside the paper conclusions, with the aim of helping professionals design more efficient and safer roundabouts, suitable to all types of vehicles.

DESIGN VEHICLE

Physical characteristics and proportions of different sized vehicles using a road, represent the key control to geometric parameter selection. Designer must evaluate traffic composition, and select the design vehicle with higher requirements in terms of dimensions and minimum turning radius. Vehicles included in Argentinean Standards (4), are as follows:

- Passenger Car (P)
- Single Unit Truck (SU)

- Intercity Bus (B12)
- Intermediate Semitrailer (WB12)
- Intermediate Semitrailer (WB15)

Categories are similar in AASHTO 2004 Green Book (5), but their dimensions are slightly different (See Table 1)

Parallel to above recommendations, is interesting to review authorized fleet limitations, included in Argentina's Transit Law (6).

Categories of current fleet division:

- Passenger Car
- Buses
- Vehicles used to freight forwarding: Simple truck, tractor trailer, Semitrailer.

Dimensions: Section 53rd included in National Transit Law (6) says as follows: "Notwithstanding a harmonious design with purposes of this law, vehicles and their cargo must not exceed the following maximum dimensions":

- WIDTH: 2.60 m (two meters with sixty centimeters).
- HIGH: 4.10 m (four meters ten centimeters).
- LONG:
- Single Unit truck: 13 m. 20 cm;
- Semitrailer: 18.60 m. (Modified from its original 18.00 meters in Decree No. 79/98);
- Tractor-trailer: 20 m;
- Tractor unit with semi-trailer (hinged) and coupled: 20 m. 50 cm.
- Intercity Bus: 14 m. In urban limit may be lower.

DIMENSION COMPARISON

Recalling what was written above, design vehicle is not intended to represent a typical average vehicle or class. It should have higher physical dimensions and grater minimum turning radius, than most vehicles of its kind.

Design vehicle dimensions included in Argentinean guidelines (4) are presented in (Table 1), in order to compare those included in ASHTO 2004 Green Book (5), and those included in Transit Law (6).

TABLE 1 Comparison of vehicle dimensions

Design Vehicle	Arg. Standards Dimension						AASHTO Dimensions						Vehicle Law 24.449	Dimensiones
					Overhang						Overhang			
	Tot Length	L1 between axles (**)	L2 between axles (**)	L between extreme axles(*)	L Raxle Rextreme	L ejeT extremo T	Tot Length	L1 between axles (**)	L2 between axles (**)	L between extreme axles(*)	L Raxle Rextreme	L ejeT extremo T		Long. Tot
BUS12	12.2			7.3	1.8	1.9	12.2	7.3	1.1	7.3	1.8	1.9		
BUS14							13.7	8.1	1.2		1.8	2.6	Bus	14
SU	9.1			6.1	1.2	1.8	9.2	6.1	1.2	6.1	1.2	1.8	SU Truck	13.2
WB12	15.2	4	7.6	12.2	1.2	1.8	13.9	3.8	7.7	12.2	0.9	0.8		
WB15	16.7	5.5	9.1	15.2	0.9	0.6	16.8	3.8	10.8	15.2	0.9	0.6	Semitrailer	18.6
WB19							20.9	6.6	12.3	18.9	1.2	0.8		
WB20							22.4	6.6	13.2 - 13.8	19.42	1.2	1.4 - 0.8		

(*) Refers to the distance called Wheelbase (WB)
(**) Distance between consecutive axles

Source: Authors.

Note: Same color matches with same dimension in order to simplify visualization and comparison.

Conclusions drawn from this chapter:

- Vehicle named in Argentinean Policy (4) as BUS12, matches with BUS12 included in AASHTO 2004 (5). However, the total maximum size allowed for a BUS in Transit Law (6) is 14m, similar to a BUS14. This vehicle has no equivalent in current Argentinean design guide.
- Vehicle type SU is coincident between standards, but again in Transit Law (6), maximum length of 13.2 m is allowed, exceeding the standard (9.2 m).
- As for the WB12, sizes match between standards, while WB15 have similar overall dimensions, changing the wheelbases. Again a difference is found regarding Transit Law (6) where 18.60 m of total length is allowed, against the 16.70 m specified for the WB15. This means that infrastructure designs are made for less demanding vehicles than those actually circulating.
- Trucks with trailer and semitrailer tractors and trailer, do not have representation in terms of design vehicle in Argentinean Design Guide (4).
- With regard to recommendations for the selection of design vehicle, In AASHTO 2004 (5), WB20 is chosen as design vehicle for intersections on highways, arterial roads, or intersections of provincial roads and industrial streets having high volume of large trucks. Argentina's primary network is designed for a WB15.
- Another conclusion that can be drawn from this final point, is the need to include in Argentina's Design Guide, better representative vehicle for a semitrailer. It should be analyzed the convenience selection of a WB19 for primary network designs. Again it would be necessary to verify the representativeness of WB15 for Argentina's fleet of heavy vehicles.

Note: AASHTO Standard, after performing the study: NCHRP 505 (6), no longer includes in the 2010th edition (8) the WB15 as a design vehicle, while in Argentina is chosen for most designs.

MODERN ROUNDABOUTS OPERATION

Vehicular Paths

Vehicles paths at roundabouts, are formed by a succession of curves with different radii and senses.

A vehicle approaching from a roundabout branch may:

- Perform a right turn (shorter movement).
- Continue in the same direction and path, circulating through about half of the circumference surrounding the central island,
- Perform a left turn, where the vehicle travels three quarters of the circumference surrounding the central island.

These paths can be seen in (Figure 1).

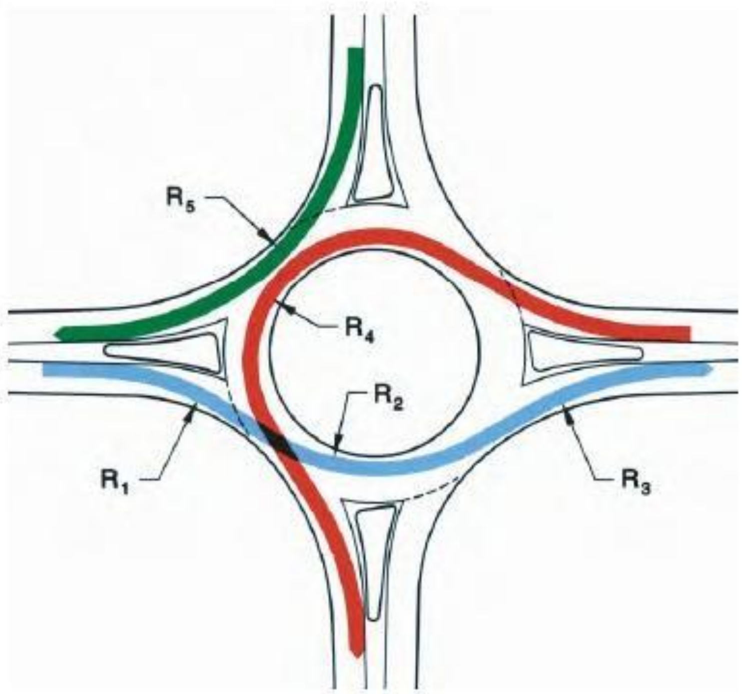

FIGURE 1 Possible movements through a roundabout. Source: NCHRP Report 672. Roundabouts an Informational Guide. Second Edition. (2)

Note in (Figure 1), that described paths will be characterized by different radii of rotation. This parameter defines also the running speed. Fastest path can be estimated considering following assumptions:

- The fastest path allowed by the geometry, is the one with softest and lesser curvature considering no interaction with other vehicle and ignoring lane markings.
- A vehicle is assumed to be 2.00 m wide and maintain a minimum clearance of 0.5 m from a roadway borderline or concrete curb and flush with a painted edge line (2)

The smaller radius along the fastest path allowed by the geometry, determines the design speed.

Speed Through The Roundabout

The relationship between the speed and the radius of the curve is given by the following formula:

$$V = \sqrt{127\,R\,(e+f)} \quad (1)$$

Where:

V = Design speed (km / h)
R = Radius (m)
e = Superelevation (m / m), usually 0.02 for entrance and exit curves and -0.02 for the curves around the central island.
f = Side friction Coefficient

This Equation from the law of the mechanics, is the basic formula that governs vehicle operation on a curve. (5)

Speed Consistency

One of the most important goals to achieve in roundabout design, is the consistency of speed for all movements . This can minimize the frequency and severity of crashes among traffic flows.

The pursued objectives are:

- Minimize relative speeds between conflicting geometric elements,
- Minimize traffic speeds between conflicting traffic streams.

This limits radii R1 to R5 shown in (Figure 1), as follows:

- On the through path R1 <R2 <R3 is desirable. Low speed at the entry of a roundabout helps to minimize control losses. When this is not possible due to topographical restrictions or road available area, the difference between R1> R2 is supposed to be less than 10 km / h.
- R4 must be such, that the difference between R1 and R4 results not greater than 20 km /h. Usually R4 is determined as central island radius plus 1.50 m and is the slowest movement. Major differences can cause control losses for circulating vehicles.
- R5 should not be associated with a higher speed than that chosen for the roundabout as a whole and not higher than 20 km / h above R4.
- The Informational Guide Second Edition of Roundabouts (2), recommends a range of 32 and 40 km / h for the speed of a single lane roundabout.

Recommended circle diameters by the FHWA Guide (2) are shown in (Table 2)

TABLE 2 Inscribed circle diameter depending on the vehicle design

Roundabout Configuration	Typical Design Vehicle	Common Inscribed Circle Diameter Range*	
Mini-Roundabout	SU-30 (SU-9)	45 to 90 ft	(14 to 27 m)
Single-Lane Roundabout	B-40 (B-12)	90 to 150 ft	(27 to 46 m)
	WB-50 (WB-15)	105 to 150 ft	(32 to 46 m)
	WB-67 (WB-20)	130 to 180 ft	(40 to 55 m)
Multilane Roundabout (2 lanes)	WB-50 (WB-15)	150 to 220 ft	(46 to 67 m)
	WB-67 (WB-20)	165 to 220 ft	(50 to 67 m)
Multilane Roundabout (3 lanes)	WB-50 (WB-15)	200 to 250 ft	(61 to 76 m)
	WB-67 (WB-20)	220 to 300 ft	(67 to 91 m)

* Assumes 90° angles between entries and no more than four legs. List of possible design vehicles is not all-inclusive.

Source: ROUNDABOUTS: An Informational Guide. Second Edition. U.S. Department of Transportation. Federal Highway Administration. NCHRP Report 672. 2010. (2)

Recommended values for key dimensions are in (Table 3)

TABLE 3 Recommended Key parameters for Modern Roundabout designs

Key Parameter	Dimensiones
1. Inscribed circle diameter	**2. 32 m to 46 m**
3. Entry width	**4. 4.2 m a 5.5 m**
5. Cirulatory roadway width	**6. 1.2 x Entry width**
7. Central island	**8. Conditioned by 1 y 3**

9. Splitter Island	**10. Min 30 m**
11. Entry radius	**12. 15 m to 30 m**
13. Exit radius	**14. 30 m to 60 m**

Source: Author, based on NCHRP Report 672. 2010 (2) recommendations.

In order to establish numerical values to R1, R2, R3, R4 and R5, as mentioned above, R4 results the diameter of the central island plus 1.5 m.

R1 can be limited so its speed, applying formula (1), results not greater than R4 in 20 km / h. The same is recommended for R5.

R2 is recommended to be greater than R1 and if that cannot be achieved, R1 should not result in excess of 10 km / h when applying the formula (1).

Obs. The diameter of the central island is calculated by subtracting to the radius of the inscribed circle, the annular road width, on their recommended minimum and maximum dimensions (5 m to 6.6 m = 120% entry width recommended range) (Table 3).

In (Tables 4 and 5) inscribed circle diameter has been selected as a basis parameter, and recommended values for R1 to R5 are tabulated. These relationships and limitations, will be used when modeling WB15 circulating paths. In (Table 4) minimum recommended circulatory roadway width of 5.00 m has been selected, in (Table 5) maximum recommended circulatory roadway width of 6.60 m has been selected.

TABLE 4. Relationships and limitations for R1, R2, R4 and R5, with circulating road width not exceeding 5 m

Base Parameter	Roadway	R4				R1 and R5				R2			
Incr. Circle diam.	anular width	R4	P	f	V	P	V+20	f	R1 p/ + 20	P	V2-10	f	R2 p/ + 10km/hs
27	5	10	-2%	0.35	20.47	2%	40.47	0.23	51.58	-2%	30.47	0.28	22.15
28	5	10.5	-2%	0.35	20.98	2%	40.98	0.226	53.75	-2%	30.98	0.343	22.9
29	5	11	-2%	0.343	21.24	2%	41.24	0.226	54.44	-2%	31.24	0.343	23.79
30	**5**	**11.5**	**-2%**	**0.343**	**21.72**	**2%**	**41.72**	**0.226**	**55.71**	**-2%**	**31.72**	**0.343**	**24.53**
31	5	12	-2%	0.336	21.95	2%	41.95	0.226	56.33	-2%	31.95	0.27	25.44
32	5	12.5	-2%	0.336	22.4	2%	42.4	0.222	58.49	-2%	32.4	0.27	26.16
33	5	13	-2%	0.336	22.84	2%	42.84	0.222	59.71	-2%	32.84	0.27	26.87
34	5	13.5	-2%	0.329	23.02	2%	43.02	0.218	61.23	-2%	33.02	0.265	27.78
35	5	14	-2%	0.329	23.44	2%	43.44	0.218	62.43	-2%	33.44	0.265	28.5
36	5	14.5	-2%	0.329	23.85	2%	43.85	0.218	63.61	-2%	33.85	0.265	29.2
37	5	15	-2%	0.322	23.99	2%	43.99	0.214	65.12	-2%	33.99	0.26	30.12
38	5	15.5	-2%	0.322	24.38	2%	44.38	0.214	66.28	-2%	34.38	0.26	30.82
39	5	16	-2%	0.322	24.77	2%	44.77	0.214	67.45	-2%	34.77	0.26	31.52
40	5	16.5	-2%	0.315	24.86	2%	44.86	0.214	67.72	-2%	34.86	0.26	32.44
41	5	17	-2%	0.315	25.24	2%	45.24	0.21	70.07	-2%	35.24	0.255	33.15
42	5	17.5	-2%	0.315	25.61	2%	45.61	0.21	71.22	-2%	35.61	0.255	33.85
43	5	18	-2%	0.315	25.97	2%	45.97	0.206	73.63	-2%	35.97	0.255	34.53
44	5	18.5	-2%	0.308	26.01	2%	46.01	0.206	73.76	-2%	36.01	0.25	35.45
45	5	19	-2%	0.308	26.36	2%	46.36	0.206	74.88	-2%	36.36	0.25	36.15
46	5	19.5	-2%	0.308	26.71	2%	46.71	0.206	76.02	-2%	36.71	0.25	36.84

Source: Authors.

TABLE 5 Relationships and limitations for R1, R2, R4 and R5, with circulating road width not exceeding 6.6 m

Base Parameter	Roadway	R4				R1 and R5				R2			
Incr. Circle diam.	anular width	R4	P	f	V	P	V+20	f	R1 p/ + 20	P	V2-10	f	R2 p/ + 10km/hs
27	6.6	8.4	-2%	0.365	19.18	2%	39.18	0.235	47.4	-2%	29.18	0.287	19.43
28	6.6	8.9	-2%	0.365	19.75	2%	39.75	0.235	48.79	-2%	29.75	0.287	20.2
29	6.6	9.4	-2%	0.35	19.85	2%	39.85	0.235	49.04	-2%	29.85	0.287	21.26
30	**6.6**	**9.9**	**-2%**	**0.35**	**20.37**	**2%**	**40.37**	**0.23**	**51.33**	**-2%**	**30.37**	**0.28**	**22.01**
31	6.6	10.4	-2%	0.35	20.88	2%	40.88	0.23	52.64	-2%	30.88	0.28	22.75
32	6.6	10.9	-2%	0.343	21.15	2%	41.15	0.226	54.2	-2%	31.15	0.275	23.65
33	6.6	11.4	-2%	0.343	21.62	2%	41.62	0.226	55.45	-2%	31.62	0.275	24.37
34	6.6	11.9	-2%	0.336	21.85	2%	41.85	0.226	56.06	-2%	31.85	0.275	25.28
35	6.6	12.4	-2%	0.336	22.31	2%	42.31	0.222	58.25	-2%	32.31	0.27	26.01
36	6.6	12.9	-2%	0.336	22.75	2%	42.75	0.222	59.46	-2%	32.75	0.27	26.73
37	6.6	13.4	-2%	0.329	22.93	2%	42.93	0.222	59.97	-2%	32.93	0.27	27.63
38	6.6	13.9	-2%	0.329	23.36	2%	43.36	0.218	62.2	-2%	33.36	0.265	28.36
39	6.6	14.4	-2%	0.329	23.77	2%	43.77	0.218	63.38	-2%	33.77	0.265	29.06
40	6.6	14.9	-2%	0.322	23.91	2%	43.91	0.218	63.79	-2%	33.91	0.265	29.98
41	6.6	15.4	-2%	0.322	24.3	2%	44.3	0.214	66.04	-2%	34.3	0.26	30.67
42	6.6	15.9	-2%	0.322	24.69	2%	44.69	0.214	67.2	-2%	34.69	0.26	31.38
43	6.6	16.4	-2%	0.322	25.08	2%	45.08	0.21	69.57	-2%	35.08	0.255	32.09
44	6.6	16.9	-2%	0.315	25.16	2%	45.16	0.21	69.82	-2%	35.16	0.255	33
45	6.6	17.4	-2%	0.315	25.53	2%	45.53	0.21	70.97	-2%	35.53	0.255	33.69
46	6.6	17.9	-2%	0.315	25.9	2%	45.9	0.21	72.13	-2%	35.9	0.255	34.4

Source: Authors.

Swept Path Width Based On Radio and Rotation Angles

In order to determine a magnitude for the swept path width and its variation as the radius of the curve increases, minimum turning templates have been measured as shown below. Thus, it is possible to display how the widening increases, as the rotation angle increases. Radii in the range of 12.53 m to 21 m were evaluated, in turnings from 30° to 180°, measuring swept path width every 10°. Results are shown in (Table 6)

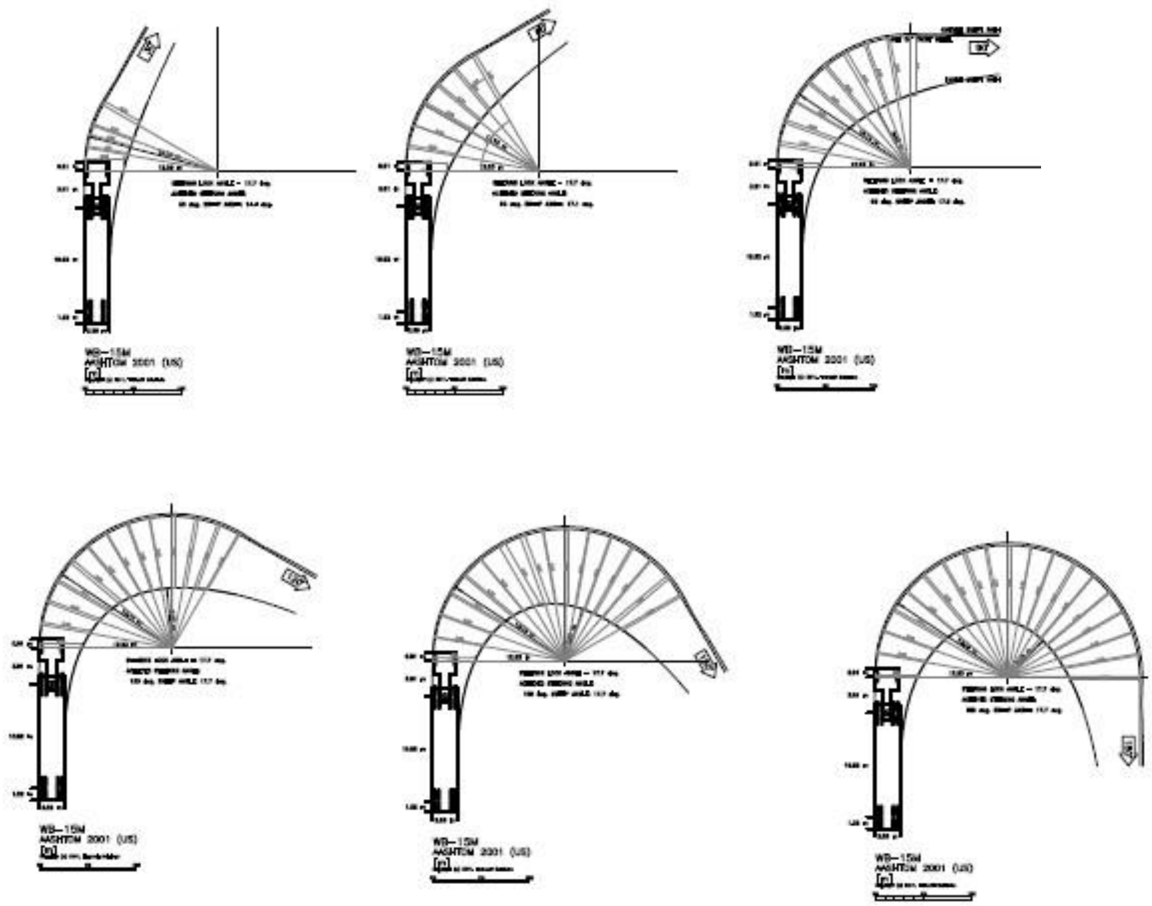

FIGURE 2 Minimum turning radius (12.53 m) templates for WB15. Turning angles of 30°, 60°, 90°, 120°, 150° and 180°. Source: Author.

TABLE 6 WB15 Swept path Widths, measured in radii range from 12.53 m to 21 m

Radio	Angle	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
12.53	30	3.98	4.3	4.39	4.23															
	60	4.37	4.95	5.41	5.66	5.73	5.63	5.34												
	90	4.37	5.06	5.62	6.08	6.43	6.64	6.73	6.69	6.48	6.1									
	120	4.37	5.06	5.62	6.11	6.52	6.87	7.16	7.36	7.47	7.46	7.34	7.09	6.66						
	150	4.37	5.06	5.62	6.11	6.52	6.88	7.19	7.47	7.71	7.88	8.01	8.05	7.99	7.82	7.52	7.07			
	180	4.37	5.06	5.62	6.11	6.52	6.88	7.19	7.47	7.71	7.92	8.11	8.28	8.41	8.47	8.46	8.37	8.17	7.85	7.37
14	30	3.89	4.25	4.35	4.18															
	60	4.13	4.75	5.23	5.53	5.6	5.5	5.17												
	90	4.13	4.78	5.32	5.77	6.12	6.36	6.47	6.43	6.22	5.8									
	120	4.13	4.78	5.32	5.77	6.15	6.47	6.73	6.94	7.06	7.07	6.95	6.67	6.21						
	150	4.13	4.78	5.32	5.77	6.15	6.47	6.74	6.97	7.16	7.33	7.45	7.51	7.48	7.29	6.98	6.47			
	180	4.13	4.78	5.32	5.77	6.15	6.47	6.74	6.97	7.16	7.33	7.48	7.61	7.71	7.79	7.8	7.71	7.52	7.18	6.65
15	30	3.8	4.21	4.32	4.15															
	60	3.9	4.63	5.11	5.41	5.51	5.41	5.07												
	90	3.9	4.64	5.17	5.6	5.94	6.19	6.31	6.27	6.05	5.61									
	120	3.9	4.64	5.17	5.6	5.95	6.24	6.48	6.69	6.81	6.83	6.72	6.43	5.95						
	150	3.9	4.64	5.17	5.6	5.95	6.24	6.49	6.69	6.87	7.01	7.13	7.18	7.15	6.99	6.67	6.15			
	180	3.9	4.64	5.17	5.6	5.95	6.24	6.49	6.69	6.87	7.01	7.13	7.24	7.33	7.39	7.41	7.34	7.16	6.82	6.31
16	30	3.74	4.17	4.3	4.11															
	60	3.83	4.52	5.01	5.32	5.43	5.33	4.97												
	90	3.83	4.52	5.03	5.44	5.78	6.02	6.15	6.12	5.9	5.45									
	120	3.83	4.52	5.03	5.44	5.78	6.05	6.27	6.46	6.58	6.61	6.5	6.22	5.72						
	150	3.83	4.52	5.03	5.44	5.78	6.05	6.27	6.46	6.61	6.74	6.84	6.9	6.87	6.72	6.41	5.88			
	180	3.83	4.52	5.03	5.44	5.78	6.05	6.27	6.46	6.61	6.74	6.84	6.92	6.99	7.05	7.08	7.02	6.88	6.51	5.97
17	30	3.72	4.14	4.27	4.08															
	60	3.72	4.42	4.91	5.23	5.35	5.25	4.87												
	90	3.72	4.42	4.92	5.32	5.63	5.87	6	5.98	5.76	5.29									
	120	3.72	4.42	4.92	5.32	5.63	5.88	6.09	6.25	6.37	6.41	6.31	6.03	5.62						
	150	3.72	4.42	4.92	5.32	5.63	5.88	6.09	6.25	6.39	6.49	6.58	6.63	6.62	6.49	6.17	5.64			
	180	3.72	4.42	4.92	5.32	5.63	5.88	6.09	6.25	6.39	6.49	6.58	6.65	6.7	6.75	6.78	6.74	6.58	6.25	5.71
18	30	3.63	4.11	4.25	4.05															
	60	3.69	4.33	4.82	5.14	5.28	5.17	4.79												
	90	3.69	4.33	4.82	5.2	5.5	5.73	5.88	5.64	5.63	5.15									
	120	3.69	4.33	4.82	5.2	5.5	5.73	5.92	6.06	6.17	6.22	6.13	5.86	5.35						
	150	3.69	4.33	4.82	5.2	5.5	5.73	5.92	6.06	6.18	6.27	6.34	6.4	6.4	6.27	5.97	5.43			
	180	3.69	4.33	4.82	5.2	5.5	5.73	5.92	6.06	6.18	6.27	6.34	6.4	6.45	6.49	6.51	6.49	6.35	6.03	5.48
19	30	3.58	4.07	4.21	4.02															
	60	3.62	4.25	5.06	5.2	5.1	4.7													
	90	3.62	4.25	5.1	5.38	5.59	5.73	5.72	5.51	5.02										
	120	3.62	4.25	5.1	5.38	5.6	5.76	5.9	6	6.04	5.96	5.7	5.18							
	150	3.62	4.25	5.1	5.38	5.6	5.76	5.9	6	6.06	6.14	6.18	6.19	6.08	5.79	5.25				
	180	3.62	4.25	5.1	5.38	5.6	5.76	5.9	6	6.06	6.14	6.18	6.19	6.22	6.25	6.28	6.26	6.14	5.84	5.29
20	30	3.53	4.04	4.2	3.99															
	60	3.55	4.19	4.65	4.98	5.13	5.03	4.62												
	90	3.55	4.19	4.65	5.01	5.27	5.47	5.6	5.39	4.91										
	120	3.55	4.19	4.65	5.01	5.27	5.47	5.63	5.74	5.83	5.88	5.81	5.56	5.04						
	150	3.55	4.19	4.65	5.01	5.27	5.47	5.63	5.74	5.83	5.9	5.95	5.99	6	5.91	5.63	5.09			
	180	3.55	4.19	4.65	5.01	5.27	5.47	5.63	5.74	5.83	5.9	5.95	5.99	6.02	6.05	6.07	6.06	5.95	5.67	5.12
21	30	3.49	4.01	4.18	3.96															
	60	3.51	4.13	4.58	4.91	5.06	4.96	4.55												
	90	3.51	4.13	4.58	4.92	5.17	5.36	5.49	5.29	4.8										
	120	3.51	4.13	4.58	4.92	5.17	5.36	5.5	5.6	5.68	5.73	5.67	5.43	4.91						
	150	3.51	4.13	4.58	4.92	5.17	5.36	5.5	5.6	5.68	5.74	5.78	5.82	5.83	5.75	5.49	4.95			
	180	3.51	4.13	4.58	4.92	5.17	5.36	5.5	5.6	5.68	5.74	5.78	5.82	5.84	5.86	5.88	5.87	5.78	5.51	4.97

Source: Author

Conclusions drawn from this chapter:

- The maximum swept path width results for angles between 110 ° and 130 °, demonstrating that R4 is the most critical movement and conditions circulatory roadway width and mountable apron. (Maximum swept path widths are highlighted in gray)
- Highlighted blue cells need mountable apron, when considering a WB15 performing turning movements, with its outer wheel closest to the outer curb (which does not occur in practice), for circulatory roadway widths of 6.60 m (maximum recommended), with inner tire 0.50 m offset from the curb.
- Evaluating circulation paths, built as recommended in Roundabout Guide (2), with clearances of 0.5 m from curbs, means that apron width can be calculated begging with swept path widths from (Table 6) subtracting vehicle width (2.60 m) and 0.50 m of clearance (or circulatory chosen with).

Swept Path Width In Terms Of Speed

In previous section swept path widths depending on the turning radius was presented. Here, the modeling is performed in function of speed. Turning movements of 180° were modeled, changing speed operation from 15 km / h to 50 km / h. (Table 7) was developed, including the outer edge, centerline and inner edge radii of vehicle swept path with. The difference between them was calculated in order to obtain maximum swept path width at the indicated speed. The superelevation for this turn (R4), has been selected as -0.02, as it is done against cross slope.

TABLE 7 Swept path width for WB15 depending on turning speed

	Superelevation	Side friction	Speed	Int tire radius	Centerlin radius	Ext tire radius	Ext ovehang radius	Steering	Max Articulation	ExtV - Int	Ext - int	Ext - Eje	Eje - Int	V^2 / 127 (i + p)
		1	2	3	4	5	6	7	8	(6 - 3)	(5 - 3)	(5 - 4)	(4 - 3)	
WB15	-0.02	0.35	15	3.74	12.53	13.69	13.97	17.7	70°	10.23	9.95	1.16	8.79	5.37
		0.35	20	3.74	12.53	13.69	13.97	17.7	70°	10.23	9.95	1.16	8.79	9.54
		0.31	25	10.82	16.68	17.87	18.09	17.7	70°	7.27	7.05	1.19	5.86	16.97
		0.28	30	23.43	27.26	28.46	28.6	17.7	70°	5.17	5.03	1.2	3.83	27.26
		0.25	35	38.11	41.05	42.26	42.35	17.7	70°	4.24	4.15	1.21	2.94	41.94
		0.23	40	57.59	59.99	61.21	61.27	17.7	70°	3.68	3.62	1.22	2.4	59.99
		0.21	45	81.84	83.92	85.14	85.18	17.7	70°	3.34	3.3	1.22	2.08	83.92
		0.19	50	113.93	115.79	117.01	117.05	17.7	70°	3.12	3.08	1.22	1.86	115.79

Source: Author

(Turnings modeled at different speeds available at request).

Conclusions drawn from this chapter:

- The swept path width decreases as the speed of the maneuver increases.
- The widening must be arranged on the inner side.
- Centerline radius for a turn performed at a speed over 25km / h, are incompatible with the range given in (Table 2) for the inscribed diameter (max 46 m). Although the fastest path is evaluated for through or right turn movements, a WB15 should not exceed 25km / h when turning left.

Methodology for Modeling Paths Analysis.

Construction of vehicle paths:

Constructed paths are for: right turn, through movement and left turn.

Note first, that a WB15 width is greater than 2.0 m, then 2.60 m is adopted. Second, the achievement should be that the vehicle does not tread any non-mountable curb or outer edge of the circular island. In case it does, this means that an apron should be provided.

A parallel tangent polygonal is built, with 0.50 m clearance from arcs that define the edge of road or curbs. Civil 3D was used to construct centerlines, **assigning** fr**ee curves**, and a waypoint at distances described in section: (Vehicular Paths).

Obs. Special attention should be paid to the truck ability in performing the required maneuvers, considering maximum articulation and angle between tractor and trailer.

There are infinite possible combinations for the same path. In this case, constructed centerlines attempt to remain within the limits of the road.

Obtaining theoretical speed profile for each path.

a. With paths outlined in the previous section, instantaneous radios can be identified and the speed can be calculated at each point. The formula is the one described in section: (Speed through the roundabout)

b. Values of side friction are adopted as recommended in point 6.7.1.2 from the Roundabout Informational Guide, FHWA (2). (Note that at this point of paths assembly, the speed is not evaluated yet, so the process is iterative, until the value of the side friction is the one that corresponds to the calculated speed).

Analysis of speeds consistency depending on guidelines set in section (Speed consistency), Analysis of results and conclusions.

Modeling process will be held for heavy trucks circulation scenarios, using recommended parameters in order to evaluate whether path widths can be accommodated in roadway width, and to check speed consistency.

Path Construction for WB15.

Through-path

Construction of Through-path (Figure 3):

- Line parallel to the approach splitter island, at least 1.30 m from the curb. It is the entry tangent of the curve R1,
- Circular curve radius R1,
- Line or transitions between V1 and V2, it is the R1 exit tangent and entry tangent for R2. Then it conditions both curves,
- Circular curve radius R2,
- Line or transitions between V2 and V3, it is the R2 exit tangent and entry tangent for R3. So it conditions both curves,

• Line parallel to the exit splitter island, at least 1.30 m from the curb. It is the exit tangent of the curve R3.

In (Figure 3) below, the assembled polygonal is shown. V1 can move over the horizontal, but its movement influences the line from V1 to V2, influencing R2 itself. Same occurs with line V2-V3.

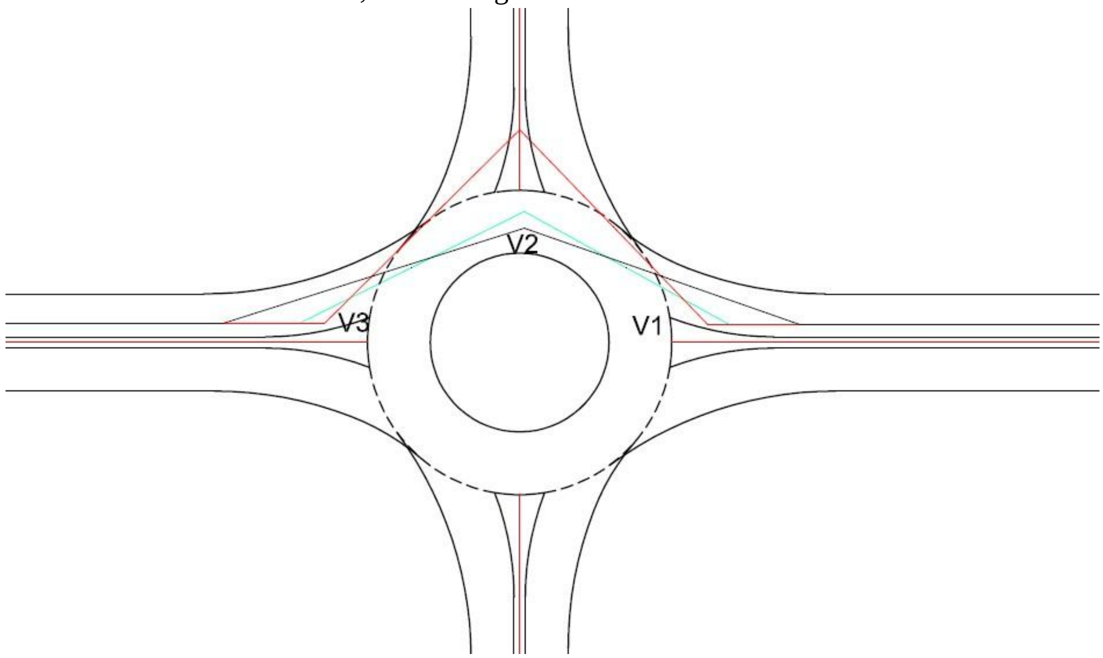

FIGURE 3 Polygonal (V1-V2-V3) to evaluate different through paths in a modern roundabout. Source: Author.

V2 can move over the vertical line and V3 through the horizontal as V1. A wide range of R1, R2 and R3 were modeled and different polygonal as well, taking above relationships into account. Clearly, depending on the chosen radius and the position of the tangents, the swept path widths vary and also the associated speed.

Several paths have been built using AutoCad, Civil3D and an application to evaluate swept path widths, in order to understand and compare how they impact on the swept path width of the road. The modeling has been performed for different radii of inscribed circle from 32 m to 46 m and for different polygonal with changing R1, R2 and R3.

Left turn path

Construction of left turn path (Figure 4):

• Line parallel to the approach splitter island, at least 1.30 m from the curb. It is the entry tangent of the curve Ra,
• Circular curve radius Ra,
• Line or transitions between V1 and V2, it is the Ra exit tangent and entry tangent for R4. So it conditions both curves,
• Circular curve radius R4,
• Line or transitions between V2 and V3, it is the R4 exit tangent and entry tangent for Rb. So it conditions both curves,

- Line parallel to the exit splitter island, at least 1.30 m from the curb. It is the exit tangent of the curve Rb.

Obs. Ra, R4 and Rb are distinguished from R1, R2, R3.

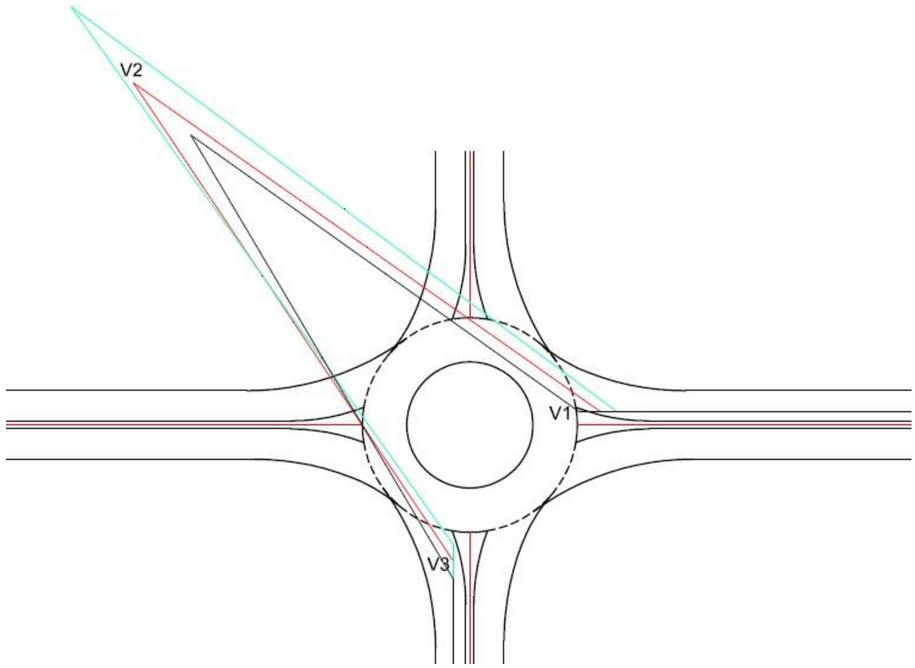

FIGURE 4 Polygonal (V1-V2-V3) to evaluate different left turn paths in a modern roundabout. Source: Author.

In this case V1 can move on the horizontal, influencing the tangent from V1 to V2. Likewise, V2 shall move within an area that allows for R4 values compatible with the design vehicle turn, and V3 moves in a vertical perpendicular to the line on which moves V1.

Again using AutoCad, Civil3D and an application to evaluate swept path widths, a succession of paths have been built, in order to understand and compare how they impact on the swept path width of the road. The modeling has been performed for different radii of inscribed circle from 32 m to 46 m and for different polygonal with changing Ra, R4 and Rb.

Obtaining Theoretical Speeds Profile

For each modeled path, the speed associated with the radius of each R1, R2, R3, Ra, R4, Rb and R5 was calculated, to verify their coherence. An example of the results are shown in (Table 8).

TABLE 8 Speed calculation associated to Ra, R4, Rb in a left turn

	No.	Type	Length	Radius	Delta angle		p	V	f			ΔV
	1	Line	50.241m					(km/hs)				(km/hs)
Ra	2	Curve	17.836m	29.051	035.1755 (d)		0.02	32.42686	0.265			
	3	Line	6.172m								V4 - Va	-17.4269
R4	4	Curve	36.044m	12.995	158.9149 (d)		-0.02	15	V maniobra			
	5	Line	2.793m								Vb - V4	23.28941
Rb	6	Curve	25.652m	43.562	033.7394 (d)		0.02	38.28941	0.245			
	7	Line	70.045m									

Source: Author

Tables like (Table 8) were drawn for each constructed path, observing weather the vehicle performs the maneuver within the roadway or not.

(Modeled paths and consistency speed tables are available at request).

It was thus possible to distinguish, the paths where the vehicle stepped Central Island or the shoulder due to the entry and exit radius. (Figure 5)

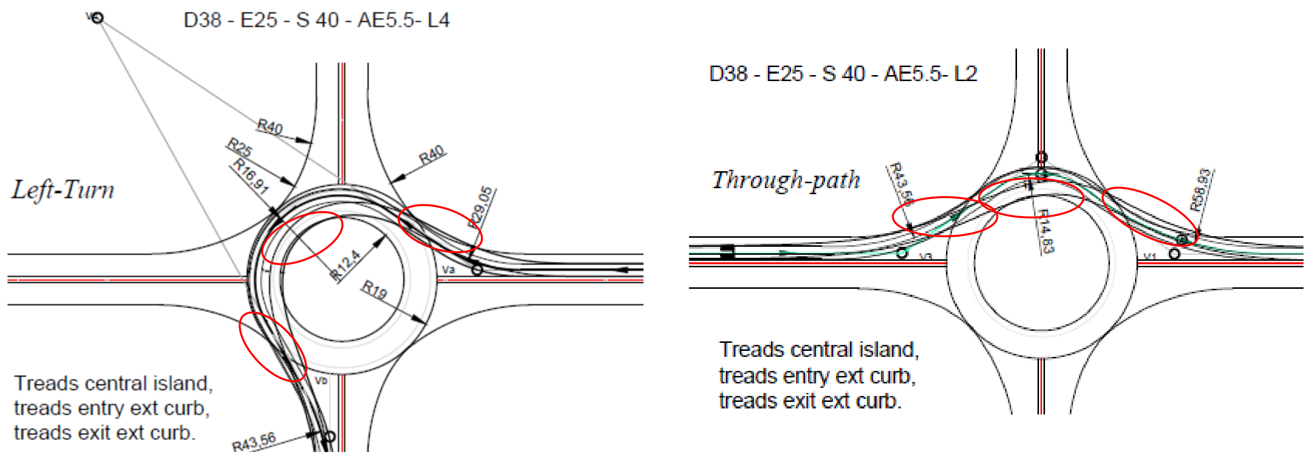

FIGURE 5 Left Turn and Through path evaluation. Source: Author.

CONCLUSIONS

- Modeling WB15 paths and subsequent verification of their associated speeds, showed in all cases speed coherence.
- For large radii diameter of inscribed circle, in order to reduce the width of the mountable apron, R4 can be taken greater than what would happen to a passenger car (central island radio + 1.50 m).
- In order to keep WB15 swept path width within the circulating roadway, R2 takes values in the range of R4.
- It was not possible to build paths where R1 <R2, because R2 is held in small ranges as noted in the previous point. The adoption of R1 < R2, means to adopt it arbitrarily, when the method establishes that the path should be the most comfortable for drivers, what means adopting the largest radii allowed by the geometry.
- Considering through-path as the fastest path within a roundabout, in any case speed associated to R2 resulted higher than 28 km / h, then WB15 vehicles should not circulate a roundabout at higher speeds. This fact was also mentioned as a conclusion from (Table 7), which means the signalization should be designed in consequence. Delta associated to R2 is commonly between 70° and 80°.
- Modeled circulating paths for roundabouts diameter between 32 m to 46 m, proves that preliminary layouts of modern roundabouts can be designed using tables developed for swept path width in function of the radius and angle of rotation (Table 6). Demonstrating that Delta associated with R4, ranges between 150 ° and 160 °(swept path width for 130° should be adopted), so as shown in (Table 6), from turning radius of 18 m, and circulatory roadway widths of 6.6 m (maximum recommended), the swept path widths are fitted between the edges. For smaller radii, mountable apron will always be needed.

- Mountable apron width for a WB15 can be determined from (Table 6). Maximum swept path width for selected inscribed circle can be determined. Then, subtracting circulatory roadway to previous measure, the result is the recommended apron width.
- Due to modeling process, is proved that Delta associated to R1 goes from 30° to 40°. From entry radius of 25 m and entrance width of 5.50 m, is possible to accommodate the approach of a WB15 between the edges of the road (swept path width at the entry). For smaller radii or entry width (recommended values are smaller), paved shoulders should be provided, in order to absorb extra swept path width. If curbs are arranged at the outer edge, they should be mountable.

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