

**DESIGN GUIDELINES FOR TURBO ROUNDABOUT BASED ON INTERSECTION
SIGHT DISTANCE TO CIRCULATING CONFLICTING VEHICLE**

By

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Abstract

Turbo Roundabout is a roundabout provided with spiral circulatory roadways for effectively counteracting the problems of modern multilane roundabout. This roundabout has an edge over modern roundabouts regarding capacity and safety and was first developed by Professor Fortujin in 1996. Turbo roundabouts are present in large percentage in Europe and is still in developing phase in North-America. Although in all the guidelines nothing has been mentioned about one important parameter of roundabout i.e. visibility. Visibility or Sight distance helps us to shape the geometry of intersection and aids in safety. In this paper sight distance analysis is going to be analysed on turbo roundabouts with a focus on Intersection Sight Distance to circulating conflicting vehicle. The traditional graphical approach has been supplemented with the analytical solution consisting of derivation of generalized mathematical equations for intersection sight distance for conflicting circulating vehicle at turbo roundabout.

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1.0 Introduction

Roundabout, although to a layman is mere a circular unsignalized intersection, is largely popular in Europe. Despite its popularity in Europe it had its origins in Washington D.C where first circular Intersection was developed in DuPont (Pumphrey, C. (2018, March 08) Rapid fruitful improvements in roundabout designs took place in Europe while North America was still struggling to cope up traffic congestions and delays by use of conventional large diameters rotaries and traffic circles. Public resistance became hindrance in switching over to these safer options but in the last two-decades North America has managed to learn from its mistakes and is now rapidly replacing the signalised intersections with small diameters roundabouts. Out of total 400 roundabouts built in Canada since 1990 around 100 roundabouts have popped up alone in Quebec (Bailey, S. (2016, October 13). Roundabouts are increasing because their provision has been identified as highly safety treatment compared to signalised intersection. They are believed to have brought advantage not only in safety, delay, emissions and fuel savings but also provide alternative to low volume or high-volume traffic as they do not require phasing plans. They also add a dimension of aesthetics, which is not there in case of signalised intersections. Most of the roundabouts constructed and working are single lane roundabouts which are managing the traffic operations perfectly but when the congestion on roundabouts increases we switch over to multi-lane roundabouts. The need of multilane modern roundabout arises when single lane roundabout is not able to handle the capacity of traffic volume the intersection offers. We know that single lane roundabouts have many advantages as compared to signalised intersection but when this single lane roundabout is converted into multi-lane roundabouts lot of safety and capacity issues erupts. We are going to discuss in detail not only the issues and problems but also the possible way-outs to mitigate them. The most optimum solution for multi-lanes intersection was found to be turbo roundabouts. We, in the study to follow, will not only analyse turbo roundabout but also develop mathematical equations based on sight distance parameters which will assist as handy tools during design.

1.1 Problem with existing multi lane modern Roundabout

1.1.1 More Conflict Points

We know that Single-lane roundabouts reduced collision frequency. The collision frequency is a result of the lower number of conflict points found at roundabouts compared to traditional intersections. Roundabouts have 75 percent less conflict points than a regular intersection, illustrated in (Figure 1). The conflict points are of three types: queuing conflicts, merge and diverge conflicts and crossing conflicts (E. HAUER, January,1988.). Crossing conflicts, the most serious type of conflict, are completely eradicated at a roundabout. Reduction of severity of collisions is achieved through the elimination of crossing conflicts at roundabouts although low operating speed also mitigate the severity of collisions by providing drivers with greater reaction time for sudden manoeuvres (MDOT, November 2007). Roundabouts have only 8 conflict points as compared to the 32 conflict point in signalised intersection. But when this single lane roundabout is converted to multi-lane roundabout then the conflict point again increases to 16 which increase the risk of collision twice as compared to single roundabouts as shown in figure 1.

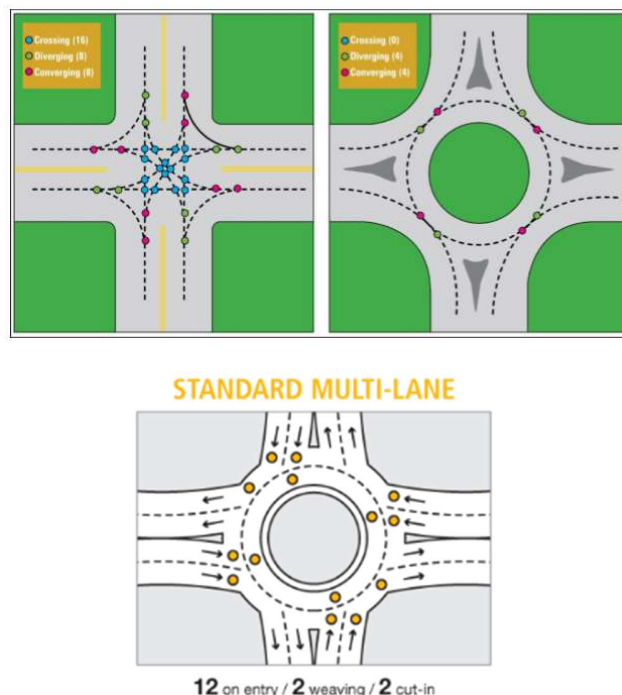


Figure 1: Conflict points in Intersection, single lane and double lane roundabout (Source: Walkability Audit Shows Promise for City. (2014, December 29))

1.1.2 Severity Of crashes

The severity of the conflict points in single lane roundabout is far less than the severity of conflict points at Intersection as they are only merging and diverging conflicts. The reason behind it is that to decrease the exiting-circulating and entering-circulating crash rates we can increase the vehicle path curvature which is fine in single lane roundabout but when the same principle is applied in case of double lane roundabout, then the vehicle sideswipe collisions increases. Furthermore, the graph (fig-2) shows that the double lane roundabout has more crashes when compared to the single lane roundabout but still the interesting thing is that the injury collisions were same as in single lane roundabout. So the conclusion was the same as conducted by NYSDOT that multi-lane roundabouts are more prone to the PDO collisions i.e. property damage only (Weber & Eng, 2007).

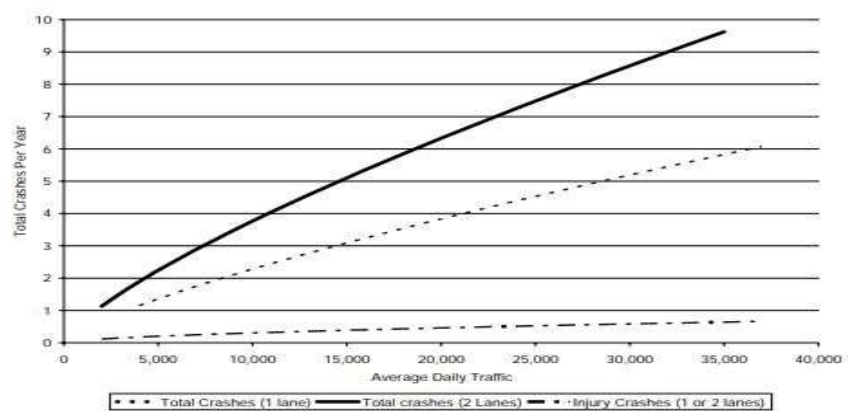


Figure 2: Graphical comparison of crashes between single lane and multilane roundabout (TRB, Transportation Research Board. (2010))

1.1.3 Maneuvering Problems

- Driver in left hand access lane has a drawback that it must change lanes over very short distance in roundabouts if he wants to exit. The situation is even worse if the roundabout has two exit lanes.
- Another principal problem is that the drivers behind the vehicle near the exit have no idea that whether the driver ahead will take an exit or will continue at roundabout.
- The final problem is reinforced by studies that show that there is very poor inner lane usage which ultimately leads to negative impact on capacity of roundabouts.

1.1.4 Driving behavior Problems

While driving on multilane roundabouts drivers do some mistake because of the driving behaviour.

The three main driving behaviour problems are:-

- Drivers fail to maintain lane position
- Drivers enter next to an exiting vehicle
- Drivers turn from the incorrect lane

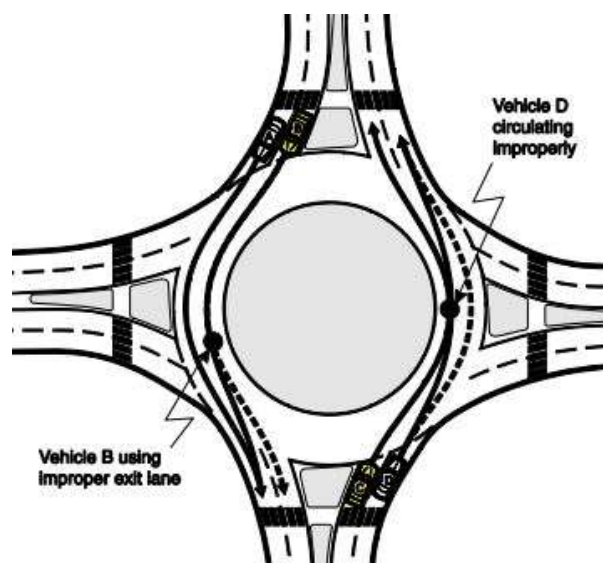


Figure 3: Drivers fail to maintain lane position (NCHRP, n.d.)

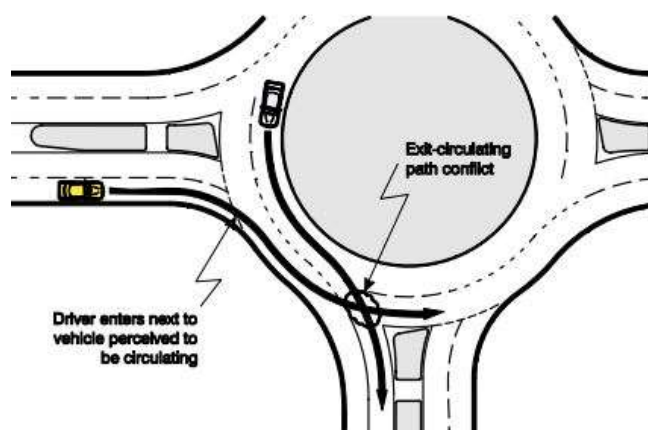


Figure 4: • Drivers enter next to an existing vehicle (NCHRP, n.d.)

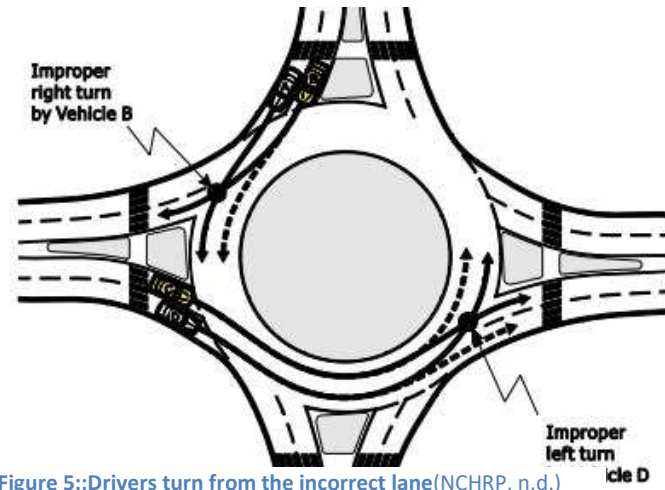


Figure 5::Drivers turn from the incorrect lane(NCHRP, n.d.)

1.2 Possible Solutions

On deeply analysing the complications of multi-lane roundabout, the solution can be a type of roundabout that separates the inner circulatory traffic with the outer circulatory traffic. Designers have devised many solutions such as flower roundabout, compact-semi-two-lane roundabout, target roundabout and turbo roundabout. We will try to briefly explain the possible solutions in the succeeding subheadings.

1.2.1 Compact Semi two lane roundabout

This type of roundabout is already in use in Germany but has not been able to extend its roots to other European nations. The concept and design of single lane roundabout is like two-lane roundabouts; the only main difference is width of the circle lane. The circle lane is made wide enough so that passengers cars which are the major percentage of traffic volume can drive side by side and trucks and buses can use the whole width of the lane. This is very simple and effective solution but still not addresses all the problems mentioned above (Tomaž Tollazzi1, n.d.).

1.2.2 Flower roundabout

To solve the above addressed problems, the only possible solution can be physically separating the lanes. Flower roundabout is one such an attempt which was developed in Slovenia. In flower roundabout right turning lanes are made depressed to achieve an efficient traffic operation and high road safety. The right turning driving vehicles have their own separated lane and the other lane becomes an inner circulatory carriageway. At reconstruction of existing two-lane roundabouts, we need not to change the position of outer road curbs, splitter islands and public lighting poles which influences the economics of the project (Tomaž Tollazzi1).

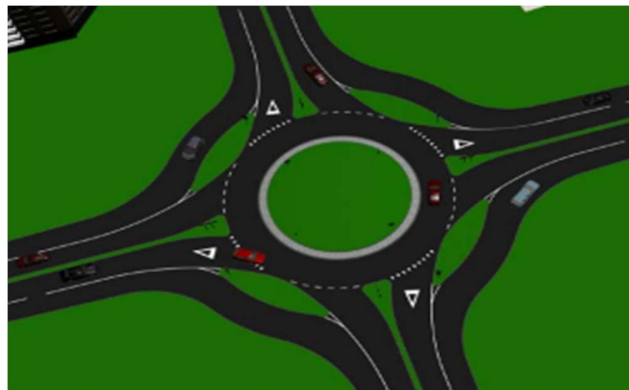


Figure 6: Flower Roundabout((Tollazzi & Engineering, 2014)

1.2.3 Turbo Roundabout

A turbo-roundabout is a moderately new sort of roundabout, which gives a spiralling stream of traffic, expecting drivers to pick their course before entering the roundabouts. Professor L.G.H. Fortuijn first presented it the late 1990's as a more efficient and safer option in contrast to the standard multi-lane roundabouts. The first turbo-roundabout was worked in the Netherlands in 2000 and turned out to be popular to the point that the Dutch government built up its very own guidelines. There are about 300 turbo-roundabouts in the Netherlands and over 390 turbo-roundabouts all around the globe (Livingston, 2014) .As in the case of other solutions turbo roundabouts also work on the same concept of separating the lane to avoid crashes. This emerged as better option as it also works with smaller radius of roundabouts. Turbo roundabout has now been adopted by some European as well as North American countries.

1.3 Scope and Objectives

Turbo roundabouts are new type of roundabouts which are perceived to be more safe and efficient and are viable solution to the problems we face in modern multi-lane roundabouts. Quite a few papers have eulogized the benefits of this Dutch invention over conventional modern roundabouts. This paper will try to shed some light on visibility aspect of the turbo roundabout.

The main objective of this paper is formulating analytical equations for sight distance at turbo roundabouts which traditionally is performed graphically. The paper will develop general analytical models for lateral clearance at multi-lane turbo knee roundabout which will be based on intersection sight distance (ISD) for circulatory vehicle. The equations will be established for two cases; the first case (Case 1) will be when the approach vehicle is at L_{\min} (15 m) before the yield line and the second case i.e. (Case 2) will be for the approach vehicle at yield line. The paper has already shed light on the problematic facts of multi-lane roundabouts and has briefly introduced the solutions to the existing problem. Furthermore, the paper will try to cover the geometric elements which shape the turbo roundabouts and will be discussed in detail in Chapter 2. Similarly, Chapter 3 explains sight distance on modern roundabouts and shows the graphical representation of sight distance on turbo roundabouts. The modelling part of the sight distances where a general sight distance and lateral clearance model is established using coordinate geometry and mathematical equations; true for all sizes of turbo knee roundabout, has been explained in chapter 4. We will end the paper by an application example in chapter 5 along with a validation section which is done through AutoCAD and will end with a conclusion in chapter 6.

2.0 Literature Review

2.1 Features of Turbo-Roundabout

The main features that separate turbo-roundabouts from modern roundabouts are:-

- More than one entry lane.
- Raised dividers are inserted to discourage drivers from cutting in.
- Roundabouts will have two lanes one for continuing at roundabouts other for exiting at roundabout.
- Design of turbo roundabouts allows us to have smaller diameter roundabouts i.e. 50 meters.
- It eliminates the necessity of weaving due to the spiral lane marking.

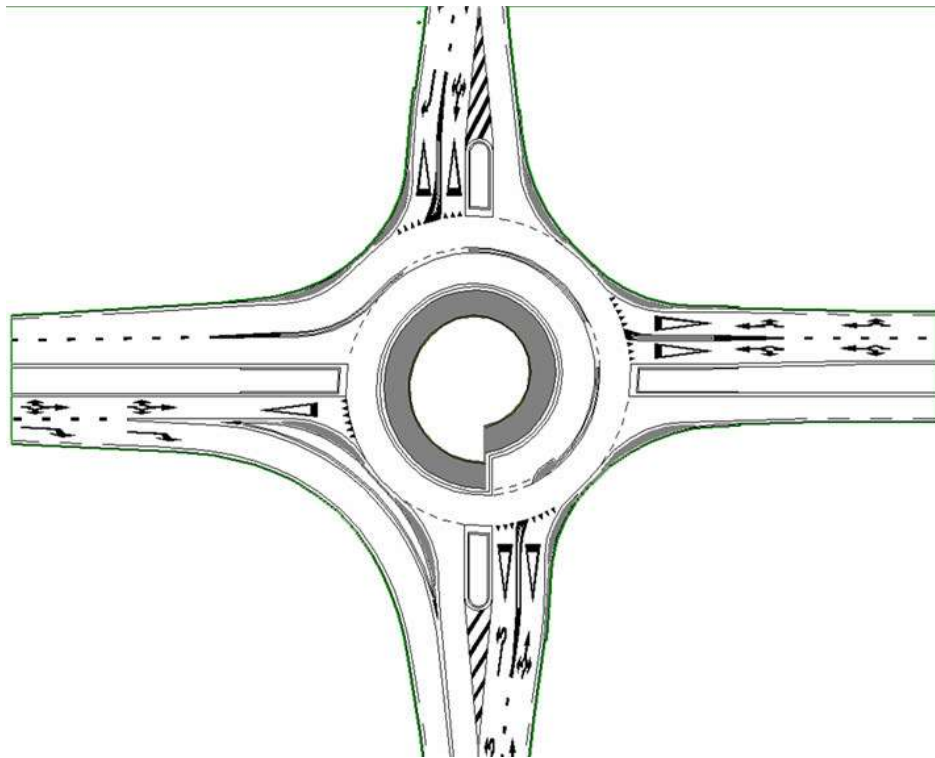


Figure 7: Layout of Turbo Roundabout(J.C. Engelsman and M. Uken, n.d.)

2.1.1 Safety Features at Turbo Roundabout

The primary objective of developing turbo roundabout was to enhance the safety at multi-lane roundabouts. The above mentioned geometric attributes give vehicle the ability to yield to only one lane instead of two lanes while entering turbo-roundabout. It is one of the biggest advantages of turbo roundabout that number of conflict points is reduced in it. The main safety features provided by the turbo roundabouts were:-

- The conflict points in multilane roundabouts were found to be 16 in case of single exit and 20 in case of two-lane exit. Turbo roundabout reduced this to just 10 conflict points (Murphy & Manager, 2015) .
- Other than that, the turbo roundabout forces drivers to have lower vehicle speeds due to narrow paths which advocate it as a safer option.
- Traffic inside the circulatory roadway has the choice of either exiting the roundabout or continue it; this does not allow weaving which ultimately reduces the conflict points.

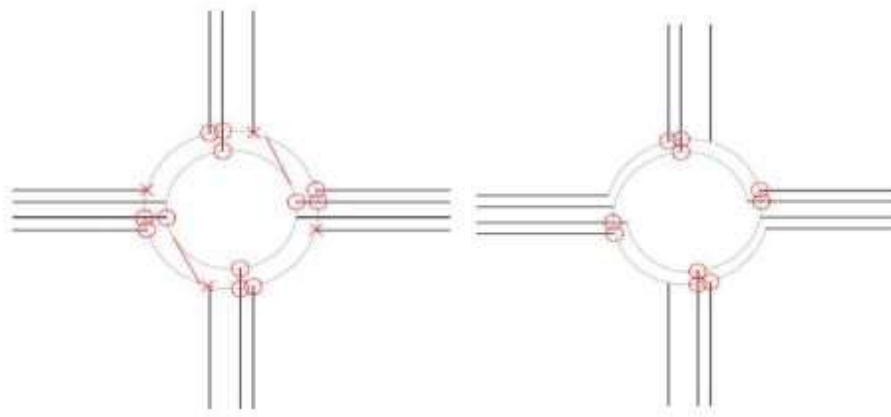


Figure 8: Conflict points in double lane and turbo roundabout(Murphy & Manager, 2015)

- This solves the principal manoeuvre problem mentioned in article 1.1 which ultimately leads to crashes. Here the problem is solved as once the driver enter the lane chosen he has a better anticipation of the movement of the vehicle in front of him, as the number of exits for both inner and outer circulatory roadway are reduced to two and that also very gradual exits in contrast to multi-lane roundabout.
- A driver behaviour problem to maintain lane position and turning to an incorrect lane which causes accidents is also solved due to the separation of lanes.

A case study was done (Murphy & Manager, 2015) where they analysed crash rates of different multi-lane roundabouts which included spiral lane roundabout, two-lane roundabout and Turbo roundabout. The location and type of roundabout on which they carried out case study has been compiled into Table 1. The source of collision data was ICBC collision data website between year 2011-2013.

Altogether there were 711 records for the multi-lane roundabouts in B.C. between 2011-2013. Table 2 bridges the recurrence of crashes by year by area. By and large, there have been around 21 crashes for every year at multi-lane roundabouts in B.C. The range was from as high as 44

Table 1: Types of Roundabout and Location (Murphy & Manager, 2015)

Location	Jurisdiction	Description
Marshall Road & Clearbrook Road	Abbotsford	Spiral roundabout (3 - 2 lane exits, 2 right turn bypass lanes)
Evans Road & Yale Road	Chilliwack	2 lane roundabout (4 - 2 lane entries, 4 - 2 lanes exists)
McCallum Road & Highway 1 Interchange	Abbotsford	2 Spiral roundabouts (both with 3 - 2 lane exits)
8th Avenue & Highway 99	Surrey	2 lane roundabout (2 - 2 lane entries, 2 - 2 lane exits)
Mount Lehman Road & South Fraser Way	Abbotsford	2 lane roundabout (3 legs, 2 - 2 lane entries, 2 - 2 lane exits)
McTavish Interchange	Sydney	2 Spiral roundabouts (2 lane entries, 2 lane exits)
16th Avenue & Westbrook Mall	UBC	Spiral roundabout (1 lane exits, 2 right turn bypass lanes)
Commercial Way & Discovery Way	Squamish	2 lane roundabout (2 lane entries, 2 lane exits)
Willingdon Road & Electra Boulevard	Victoria Airport	Turbo roundabout (knee, 3 legs, 1 - 2 lane entry, 1 - 2 lane exit)

crashes for every year at the Marshall Road and Clearbrook Road, to as low as 0.3 impacts every year at the Turbo roundabout. As far as accident recurrence, we observed that the Turbo Roundabout encountered a greatly improved road safety than any other multi-lane roundabouts. The case study further legitimatise itself by normalizing crash frequency in a way that at an intersection where there is more traffic, by logic there will be more crash frequency. To normalise, the volume of traffic at each intersection was approximated at high traffic flow for crash rate

analysis. The conclusion of the study based on data of Table-2 was very much clear that the turbo roundabout gives us far more road safety performance as compared to other multi-lane roundabouts.

Table 2: Crash rate at Roundabouts(Murphy & Manager, 2015)

Location	Crashes			Total Crashes	Crashes / Year / Roundabout	Estimated Traffic		Crash Rate (/MEV)
	2011	2012	2013			AWDT	Yearly Traffic	
Marshall Road & Clearbrook Road	38	47	48	133	44.3	25000	8750000	5.07
Evans Road & Yale Road	33	35	37	105	35.0	24000	8400000	4.17
McCallum Road & Highway 1 Interchange	95	50	45	190	31.7	28000	9800000	3.23
8th Avenue & Highway 99	26	19	38	83	27.7	18000	6300000	4.39
Mount Lehman Road & South Fraser Way	17	16	25	58	19.3	30000	10500000	1.84
McTavish Interchange	41	34	33	108	18.0	26000	9100000	1.98
16th Avenue & Westbrook Mall	16	8	3	27	9.0	15000	5250000	1.71
Commercial Way & Discovery Way	0	4	2	6	2.0	1000	350000	5.71
Willingdon Road & Electra Boulevard	0	0	1	1	0.3	4300	1505000	0.22

2.1.2 Capacity features at Turbo Roundabout

As stated earlier that turbo roundabout main feature is its safety feature but apart from it; it has been found as better at capacity aspect also when compared to double-lane roundabout. When talking about capacity a study by (Fortuijn 2009) gives the capacity formula for calculating the capacity of turbo-roundabout. Despite the detailed capacity analysis by (Fortuijn 2009) nothing significant was mentioned for heavy traffic flow. (Giuffre, Grana ,2016) tried to measure the effect of heavy vehicle flow on turbo roundabout using microsimulation tool. They tried to observe the effect on capacity at different percentages of truck vehicle in total fleet of vehicles. For which they used the concept of (PCE) i.e. Passenger Car Equivalent. The passenger car equivalent is unit used to assess the traffic-flow rate. According to (AASHTO) PCE uses private passenger car as 1 unit

and motorcycle as 0.5 unit. Our interest in this study is at heavy vehicles i.e. bus, tractor or truck for which they estimate PCE value at different percentage of heavy vehicles. (Giuffre, Grana ,2016) uses a proper methodology where after laying out the turbo roundabout geometric features using the swept path of the vehicle the circulating flow is reproduced using origin-destination matrices and capacity is analysed for two cases. The first one is for C_{car} i.e. the capacity in case of traffic demand of passenger cars only, the second case would be C_P i.e. the capacity in case of traffic demand corresponding to “P” percentage of heavy vehicles. The results then are injected in the following equation for which E_T i.e. PCE for different percentage of heavy traffic flow is estimated.

$$C_{car} = (1-P) * C_P + P * C_P * E_T$$

Where C_{car} is the capacity in case of traffic demand of passenger cars only.

C_P is the capacity in case of traffic demand corresponding to “P” percentage of vehicles.

E_T is the passenger car equivalent factor.

The results of the (Giuffre, Grana ,2016) were done for two cases; the first one for right-lane on major entries and left-lane for major entries. The results showed that a PCE of less than 2 should be used for major entries at usual heavy traffic flow i.e. 10% to 20% and at minor entries the PCE value of 4.5 can be reached for 10% to 20% heavy traffic flow. In contrary HCM suggests a value of $E_T=2$ for both the major and minor entries; so, it is overestimating effect of heavy traffic flow at major entries and underestimating at minor entries. For higher percentage of heavy vehicle traffic we can use similar methodology to estimate PCE value for particular percentage of heavy vehicles. So turbo roundabouts are effective in case of heavy vehicle flow as long as capacity of the intersection is analysed using the right passenger equivalent factor. According to the study conducted by (Giuffrè, Granà, & Marino, 2012) turbo roundabouts perform better in terms of capacity than double lane roundabout. It was observed that fewer delays are experienced by the drivers when at turbo roundabout there is high traffic volume coming from major road and low-to-medium traffic flow comes from minor roads. Another observation was that when low-to-medium traffic enters from major roads both the roundabouts i.e. turbo and double lane roundabouts perform in equivalent way in terms of capacity. Recent studies also show that capacity of turbo roundabout is found to be 25% to 35% more than two-lane modern roundabout. (Fortuijn 2009) also provides us with the formula which gives the traffic proportion used by outer and inner lane. The study also revealed one situation when two-lane roundabout has more capacity i.e. when

the proportion of right turn in minor direction is more than 60%. (Gaspar, 2013) gave three particular situations in which turbo roundabout can have improvement in terms of capacity as compared to conventional roundabout. The three situations are:-

- When there is an increase in the number of right turns on the secondary lane.
- When there is an increase in the go-ahead movement in the dominant flow.
- When there is an equilibrated traffic distribution in all arms and directions of the turbo-roundabout.

To further prove their point (Gaspar, 2013) did a case study on Baden-Powell square in Lisbon, Portugal. The result of their case study is shown in graphical form in fig (9). The graph clearly shows the entry capacity is decreased during North-South entry approach and degree of

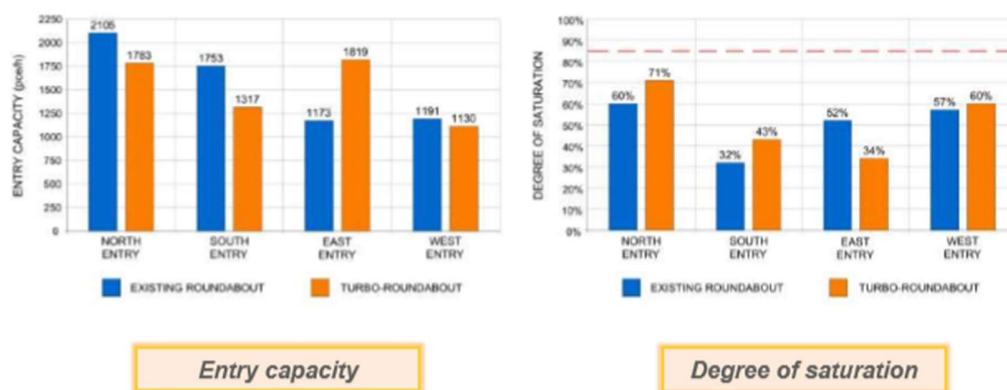


Figure 9: Case study for Capacity(Gaspar, 2013)

saturation is increased by more than 10% whilst there was a significant improvement of capacity in east entry with west entry remained approximately the same.

2.2 Geometric design of Turbo roundabout

Before digging deep into the sight distance of turbo roundabouts, the geometric design of turbo roundabout needs to be understood. As in the case of modern roundabout there are certain geometric features related to turbo roundabout such as Central Island, approaches etc. But first we need to study about different variations of turbo roundabout.(Gaspar, 2013).

2.2.1 Types of Turbo roundabout

There are different variations of turbo roundabouts. Depending on whether it is four legged or three legged the different type of turbo roundabout is chosen.

- For four-legged intersection-: egg shape, knee shape and rotor
- For three leg intersection-: star shape, stretched-knee

For four-legged intersection Rotor or Star roundabouts are used when equal flow of traffic is there from all directions and egg shape is used when there is an unbalanced flow or predominant flow from one direction (Džambas, Ahac, and Dragčević 2008). In case where there is an



Figure 10: Turbo roundabout and its geometric features(Murphy & Manager, 2015)

select an ovular roundabout which keeps the number of lanes on access road like the previous one and we don't need to extend the pavement area (Silva, Vasconcelos, and Santos 2014).

2.2.2 Central Island

There are two parts of Central Island in turbo roundabouts

- Traversable i.e. mountable
- Non-Traversable i.e. non-mountable

As in case of modern roundabout the truck apron is used for vehicles with larger swept path (USDOT, 2017). Although Croatian, Serbian and Slovenian guideline suggest that the truck apron should be used as a surface where emergency vehicles or regular vehicles in case of

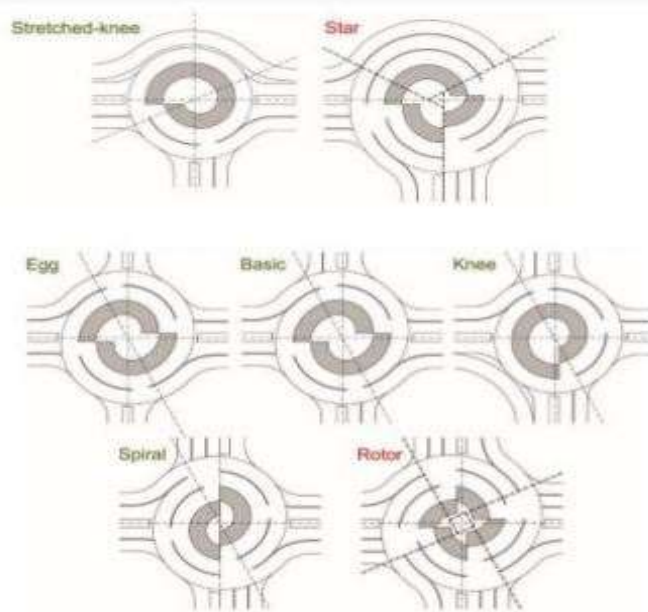


Figure 11: Types of Turbo-Roundabouts(Džambas, Ahac, & Dragčević, 2017)

emergency can stop. The traversable apron can be of width 5m which will help to accommodate vehicles larger than 22m through roundabout. The non-traversable part can be used for placing traffic signs as they have a great place in efficient functioning of turbo-roundabouts. The beginning of traversable apron can be spiral, or flat but Dutch guidelines recommend flat beginning.(Džambas et al., 2017).

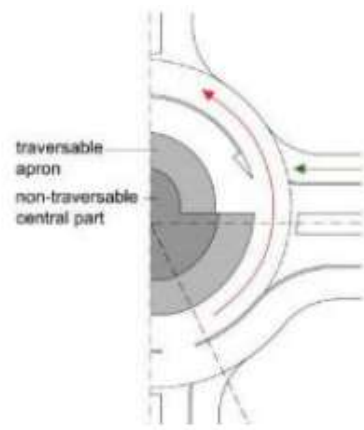


Figure 12: Central Island(Džambas et al., 2017)

2.2.3 Approaches

Turbo roundabouts are recommended to have approaches aligned at 90 degrees so that they can ease the ride ability of long vehicles. But often it becomes difficult to follow this guideline especially in case of reconstruction. The Dutch guideline does not give further solution to this problem. The following table shows the value of defining parameters of turbo-roundabout (Džambas, Ahac, and Dragčević 2008). It should be further noted that design of turbo roundabout approaches should be such that it does not exceed the maximum recommended value. Serbian and Slovenian guidelines do not recommend width of entry and exit lane. Recommendation for different parameter value feature of approaches is compiled in below

Table 3:Recommended parameter values of turbo-roundabout (Fortuijn, Lambertus G H. 2009)

Parameter	Recommended value	
Width of single lane entry lane and exit lane	Entry: 4.0m	Exit:4.5m
Width of two lane entry lane and exit lane	Entry: 3.5m	Exit:4.0m
Width of splitter Island	Dutch guideline: 2.5 Serbian guideline:2.0m	
Radius of entry and exit curve	Entry: 12m	Exit:15m

2.2.4 Design Vehicle

It has been already discussed in the earlier section that the swept path of vehicle is determining factor in design of roundabout geometry. From the Dutch experience and their popular fleet of

vehicles two axle truck with a three-axle semi-trailer is used as design vehicle. Different European guidelines have specified different vehicle dimensions which should be used as design vehicle. The following table shows the vehicle dimensions for Netherlands only as they have more experience of Turbo-roundabouts (Fortuijn, Lambertus G H. 2009).

Table 4: Design vehicles of AASTHO (AASTHO, 2001)

Metric													
Design Vehicle Type	Symbol	Dimensions (m)											
		Overall			Overhang		WB ₁	WB ₂	S	T	WB ₃	WB ₄	Typical Kingpin to Center of Rear Axle
		Height	Width	Length	Front	Rear							
Passenger Car	P	1.3	2.1	5.8	0.9	1.5	3.4	–	–	–	–	–	–
Single Unit Truck	SU	3.4-4.1	2.4	9.2	1.2	1.8	6.1	–	–	–	–	–	–
Buses													
Inter-city Bus (Motor Coaches)	BUS-12	3.7	2.6	12.2	1.8	1.9 ^a	7.3	1.1	–	–	–	–	–
	BUS-14	3.7	2.6	13.7	1.8	2.6 ^a	8.1	1.2	–	–	–	–	–
City Transit Bus	CITY-BUS	3.2	2.6	12.2	2.1	2.4	7.6	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 11	3.2	2.4	10.9	0.8	3.7	6.5	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 12	3.2	2.4	12.2	2.1	4.0	6.1	–	–	–	–	–	–
Articulated Bus	A-BUS	3.4	2.6	18.3	2.6	3.1	6.7	5.9	1.9 ^a	4.0 ^a	–	–	–
Trucks													
Intermediate Semitrailer	WB-12	4.1	2.4	13.9	0.9	0.8 ^a	3.8	8.4	–	–	–	–	8.4
Intermediate Semitrailer	WB-15	4.1	2.6	16.8	0.9	0.6 ^a	4.5	10.8	–	–	–	–	11.4
Interstate Semitrailer	WB-19*	4.1	2.6	20.9	1.2	0.8 ^a	6.6	12.3	–	–	–	–	13.0
Interstate Semitrailer	WB-20**	4.1	2.6	22.4	1.2	1.4-0.8 ^a	6.6	13.2-13.8	–	–	–	–	13.9-14.5
"Double-Bottom"-Semitrailer/Trailer	WB-20D	4.1	2.6	22.4	0.7	0.9	3.4	7.0	0.9 ^b	2.1 ^b	7.0	–	7.0
Triple-Semitrailer/ Trailers	WB-30T	4.1	2.6	32.0	0.7	0.9	3.4	6.9	0.9 ^c	2.1 ^c	7.0	7.0	7.0
Turnpike Double-Semitrailer/Trailer	WB-33D*	4.1	2.6	34.8	0.7	0.8a	4.4	12.2	0.8 ^d	3.1 ^d	13.6	–	13.0
Recreational Vehicles													
Motor Home	MH	3.7	2.4	9.2	1.2	1.8	6.1	–	–	–	–	–	–
Car and Camper Trailer	P/T	3.1	2.4	14.8	0.9	3.1	3.4	–	1.5	5.8	–	–	–
Car and Boat Trailer	P/B	–	2.4	12.8	0.9	2.4	3.4	–	1.5	4.6	–	–	–

2.2.5 Fastest vehicle path

Modern roundabouts have four critical fastest route paths and turbo roundabouts have three critical fastest route paths which helps us to analyse roundabout in perfect manner. The three critical routes are-:

- Through movement
- Right turn from outer entry lane
- Right turn from inner entry lane

All the European guidelines agree to these three paths as critical paths. However Dutch guidelines recommend the distance of 1m from the point of impact which is not safe as it does not guarantee unhindered passage of vehicle whereas when we provide minimum clearance of 2 m will result in greater curvature of vehicle path. Study by (Džambas, Ahac, and Dragčević 2008) shows that optimum minimum clearance is 1.5m. Although “Torus” software strictly followed Dutch guidelines the fastest vehicle paths on it gives no results even while analysing.

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2.2.6 Raised mountable dividers

According to study by (Tollazi,, Renčelj,) there are some countries which dismisses the idea of mountable dividers and there are some which are in support of them. The people in support of these mountable dividers advocate the fact that without raised dividers drivers tend to change from inner lane to outer lane which causes safety issues. Although theoretically mountable dividers do not have great influence over capacity and safety these dividers require winter service and regular maintenance and is also a threat for two-wheeler safety (Livingston, 2014). Dutch guidelines recommended the use of these dividers and states that the width, height and length of these dividers should be 30 cm, 7cm and 4m respectively.



Figure 13: Raised Mountable dividers((Tollazzi & Engineering, 2014)

On turbo roundabouts there should be traversable beginning as suggested by Dutch guidelines. This geometric feature prevents the inadmissible traffic flow which is further going to weaving on inner circulatory roadway.

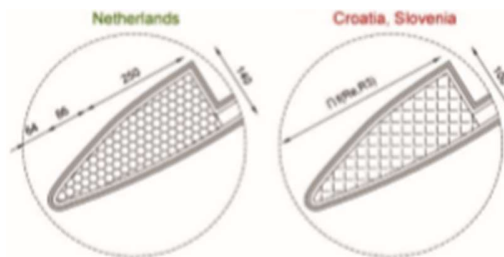


Figure 14: Traversable beginning on a mountable lane divider(Džambas et al., 2017)

The length of the mountable divider as suggested by Dutch guidelines should be 4m. In Croatian and Slovenian guidelines length of the mountable divider is not defined; there it is defined by the curvature of the entry curve radii and outer circulatory lane inner radii. The latter design approach is more feasible because it gives designer an independence to choose a length of mountable divider according to the swept path of the design vehicle. The opening width of inner circulatory roadway is not defined by any design guideline. Studies have shown that the opening width depends on the swept path, minimum clearances, inner circular radius and lane divider i.e. median width (Džambas et al., 2017).

2.2.7 Additional geometric elements added on Turbo Roundabout

2.2.7.1 Pedestrian Crossing

Many Dutch Turbo Roundabouts have two-stage pedestrian and cyclist crossing on approaches to roundabout. This two-stage crossing is also used by cyclist, although pedestrians and cyclists are segregated as we can see in fig 15.



Figure 15: Two stage pedestrian and cyclist((Murphy & Manager, 2015)

2.2.7.2 Small island Diverter

After some experience with turbo roundabout, an issue was raised. The issue was that motorists were attempting to turn left and travel in clockwise direction especially elderly people who were not able to focus on signs and symbols of road. To solve this problem a small diverter island with no left turn sign was added to turbo roundabout which provided a visual glue for drivers to turn right rather than left. Also, no further incorrect turns were made on roundabout as observed by engineers in Canada.



Figure 16: small island diverter

2.2.8 Turbo Block

The first part of making a turbo-roundabout is generation of turbo-block. A turbo block is supplementary, or guideline construction used in the design of turbo-roundabout. It is a foundation stone on which turbo-roundabout is based. The features of the turbo block give us an illusion that it would be spiral curve but instead it is a spiral-circulatory geometry consisting of two semicircles with different centres. The type of turbo roundabout mentioned in article 2.2.1 is defined by the type of turbo block; an egg roundabout has two starting spirals, rotor turbo roundabout has four starting spirals and the knee turbo roundabout which is our case have one starting spiral.(Gaspar, 2013). The turbo block also has a primary translation axis which is a hypothetical line usually at some angle with Y -Axis i.e. θT which serves as the border between the two semi-circles. It is designed in such a way that circular arcs at one side of translation axis overlap with circular arcs on other side. Guidelines for predefined templates of turbo roundabouts are provided by major developing European nations such as Netherlands, Croatia, Slovenia and Germany. Based on these guidelines of predetermined templates the turbo block can be classified into two groups; Group 1 will be consisting of guidelines provided by Dutch, Croatian and Slovenia whilst Group 2 will describe the guidelines provided by German documents.

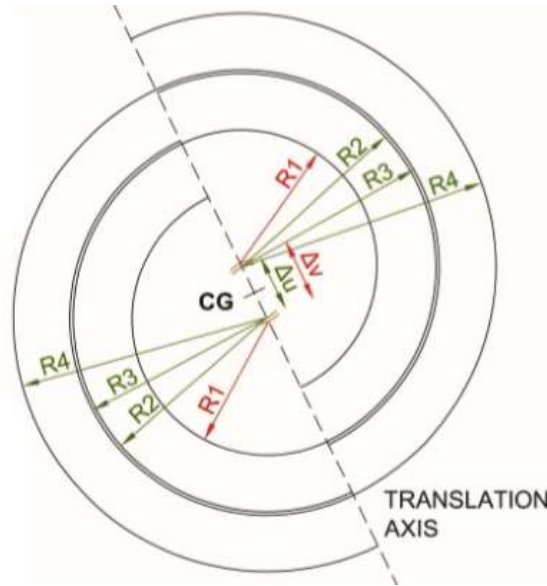


Figure 17: Turbo Block for Dutch, Croatian and Slovenia(Džambas et al., 2017)

The templates provided by these three countries consist of four circular arcs with larger radii of successive arcs. There are four centres and all of them lie on translation axis (Fig 17) Roundabout curves R_1 and R_2 represent the inward and the external edge of the internal circulatory roadway L_1 , while circular curves R_3 and R_4 represent the inward and the external edge of the external circulatory roadway L_2 (Serbian Authority for Roads, Beograd, 2012) (CROW, 2008).

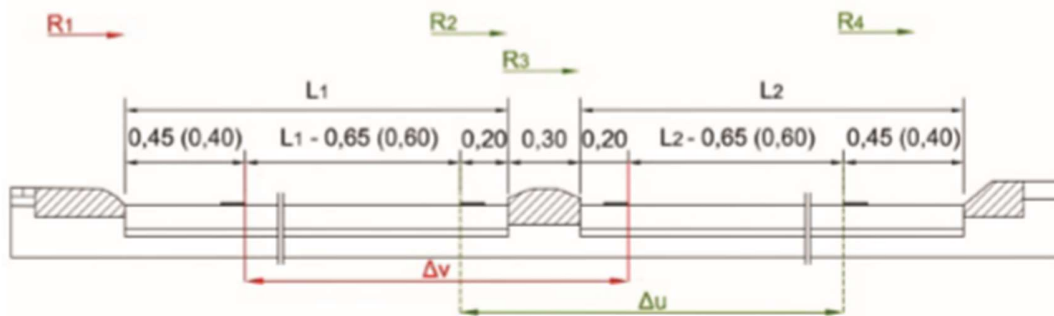


Figure 18:Cross section of Turbo Block Dutch, Croatian and Slovenia(Džambas et al., 2017)

The Dutch guideline suggests that the template of turbo roundabout should be chosen by fastest path vehicle speed and the optimum value of inner roundabout radius depends upon the dimension of splitter island (CROW, 2008).The guideline suggests that for 3m and 7m splitter island the value of inner roundabout radius is 12m and 15m respectively; smaller inner radii are recommended but

larger inner radii can be used when traffic flow demands. Furthermore, there is a shift observed “f” between the circular arcs, the shift is there due to narrow width of marginal strips and can be eliminated by widening marginal strips as done by Croatian guideline. The position of translation axis recommended by these countries guidelines is "five minutes until five" for four-leg intersections and "ten past eight" for three-leg intersections (Ministry of Transport Republic of Slovenia, 2011)

German guideline is somewhat simpler; the turbo block in German guideline suggests three pair of circular arcs and two centres on translation axis. One of centre represents circular arcs at one side of primary translation axis and other centre represent circular arcs of other side of primary translation axis. No widening is provided for German turbo-block, the width is persistent throughout. The turbo block also do not provide any template and advise that circulatory lane, width and other geometric features depends upon design vehicle and swept path of the vehicle; although it recommends the range of diameter from 45m to 70m. The position of translation axis according to German document is an iterative process which depends on design vehicle and position of approaches (FGSV, 2015).

2.2.9 Movement of traffic flow in turbo roundabouts

Not much has been mentioned in the studies about the movement of traffic flow in turbo roundabouts, which may be due to the simple and understandable mechanics of it. Although it is recommended that we provide signage as during driving on turbo roundabouts, it is very critical which lane to choose depending upon the destination.(Gaspar, 2013)

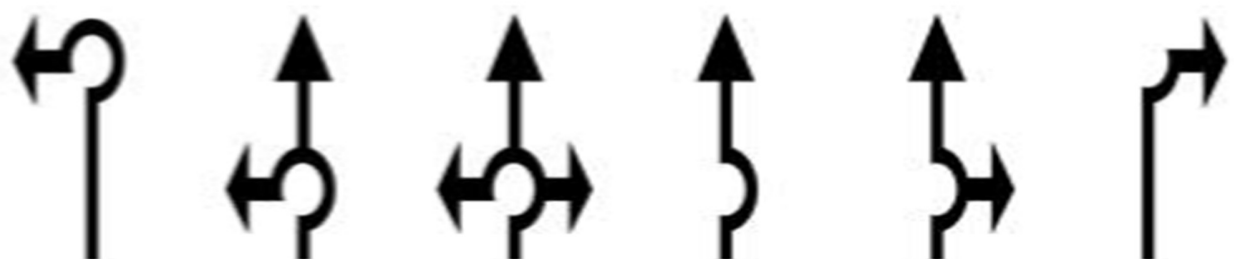


Figure 19: Signage (Gaspar, 2013)

Fig 19 demonstrates movement of a vehicle from approach 1 to all other approaches and movement from other approaches will be similar.

An important aspect of movement of vehicles at turbo-roundabouts is the swept path of the vehicle. This swept path helps us to decide the radius of the turbo block and show us that the vehicle is safe to manoeuvre through that intersection. Referring to table 4; heavy vehicles which included “Long combination vehicles” i.e. WB-20D, WB-30T and articulated buses i.e. A-BUS were analysed on Auto-Turn Pro. Using Auto-Turn Pro we observed the swept path of the vehicles and following results were obtained.

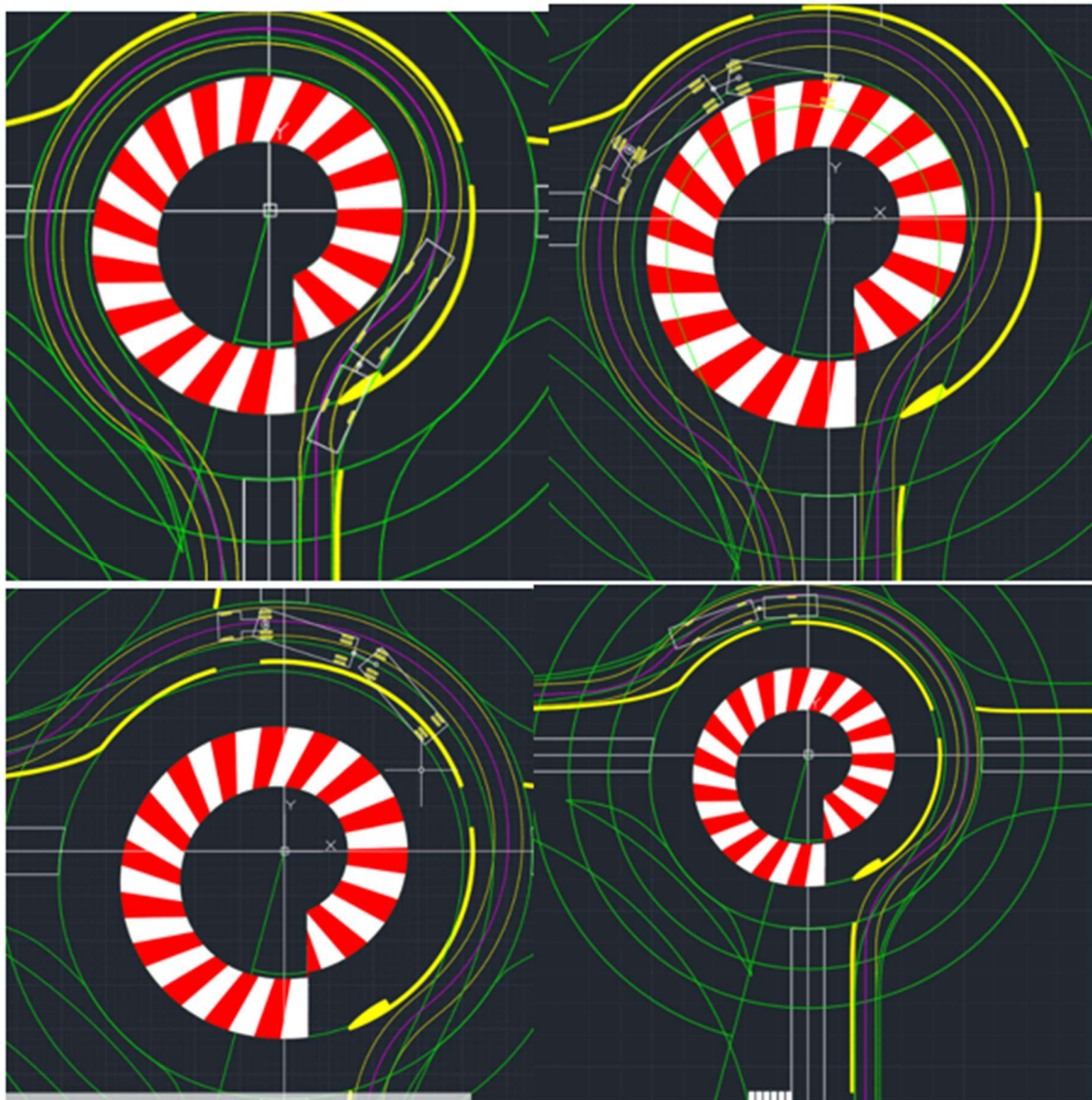


Figure 20: Swept path of the vehicles clockwise A-BUS at inner circulatory lane, WB-20D at inner circulatory lane, A-BUS at outer circulatory lane, WB-20D outer circulatory lane

As we can see in fig-20 that both long combination vehicles i.e. WB-20D and articulated buses i.e. A-BUS can manoeuvre safely but take space of geometric feature such as raised mountable divider and truck apron. As shown in fig-20; WB-20D used truck apron at inner circulatory lane and raised mountable divider while travelling outer circulatory lane. Whilst A-BUS never stepped on truck apron at inner circulatory lane but it used raised mountable divider that also just at start to enter the opening. Study by (Gazzarri, A., Pratelli, A., Souleyrette, R. R., & Russell, E. R.) confirms that for heavy vehicles especially for turbo roundabouts these features are required as high occupancy vehicles requires additional turning space as compared to passenger car. So long combination vehicles and articulated buses can manoeuvre safely due to the geometric feature of raised mountable divider and truck apron.

3.0 Sight Distance

Sight distance is an integral part while designing any intersection. Sight distance is the distance available for the driver to safely drive the vehicle so that he can see the stationary or moving objects and will allow doing the safe manoeuvre. Sight distance at roundabouts is provided to enable a driver without the right of way to enter a roundabout traffic flow in secure manner. Geometric elements of roundabouts are of key importance in providing sight distance(Washington State Department ofTransportation, 2017). At roundabouts the important sight distances which will influence its design are:-

- Stopping sight distance
- Intersection sight distance.

3.1 Stopping Sight Distance in Roundabouts

Stopping sight distance (SSD) is the minimum sight distance available on a highway at any spot having sufficient length to enable the driver to stop a vehicle travelling at design speed, safely without collision with any other obstruction. The sight distance ensures that a driver can clearly see the obstacles or potentially conflicting vehicles. Sight distance at unsignalized intersection i.e. roundabouts is provided to enable a driver to enter a roundabout traffic flow without the right of way in secure manner; so the geometric elements of roundabouts are of key importance in providing sight distance. Sight distance can be defined the distance that allows the driver to stop safely if something happens unexpectedly. Stopping sight distance is the sum of the distance travelled during the perception time, reaction time and the breaking distance. For a levelled road this is obtained by equating the work done in stopping the vehicle and the kinetic energy of the vehicle. Stopping sight distance should be measured assuming driver eye height 3.54 ft and an assumed object height of 1.97 ft according to (AASHTO), 2004) There are 3 critical locations according to mentioned references in which we must check stopping sight distances for roundabouts -:

- Approach Sight Distance
- Exit Cross Walk Sight Distance
- Circulatory Sight Distance

3.1.1 Approach sight distance

It is the stopping sight distance required for the approaching vehicle before entering the roundabout. Approach sight distance is analysed when a vehicle is at the approach curve i.e. perpendicular to the tangent of the inscribed circle. On deeply analysing the approach sight distance it is further subdivided into two sections that is sight distance to crosswalk and sight distance to yield line.(USDOT, 2017)

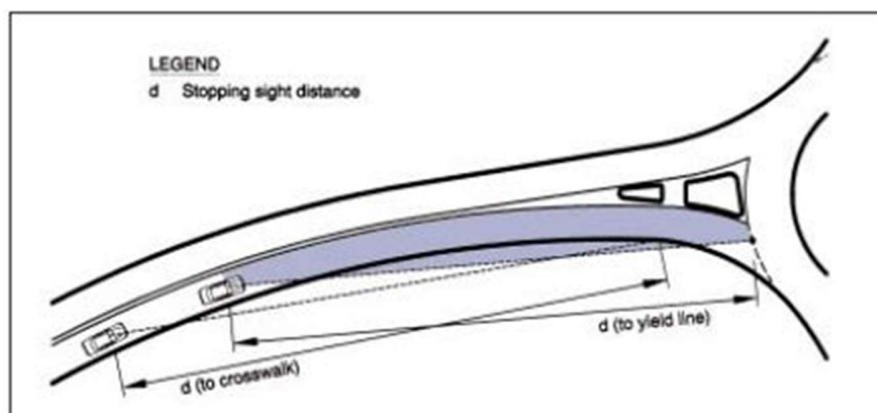


Figure 21: Approach sight distance (USDOT, 2017)

3.1.2 Exit crosswalk sight distance

It is the stopping sight distance needed towards the crosswalk on exit of the circulatory roadway. A cross walk sight distance is critical for pedestrians and is assumed to be perpendicular to the curve and is computed for both entry and exit of the vehicle(USDOT, 2017)

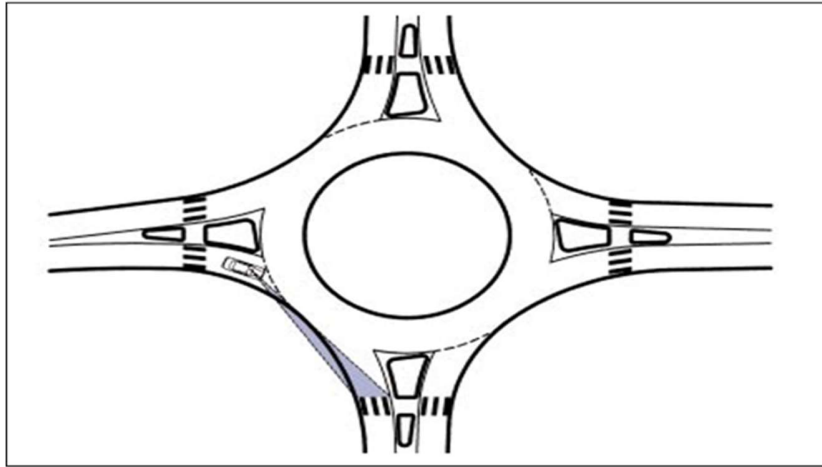


Figure 22: Exit cross walk sight distance (USDOT, 2017)

3.1.3 Circulatory sight distance

It is the stopping sight distance required on the circulatory roadway to drive the vehicle safely. The circulatory sight distance is important as the driver must pay attention to the left roundabout quadrant, to safely drive and driver also needs to have an adequate sight distance in front of vehicle. The design stopping sight distance is measured along the vehicle's path as it follows the curvature of the roadway and is not measured as a straight line. So this is the reason for using stopping sight distance on the curves and not on straight paths.

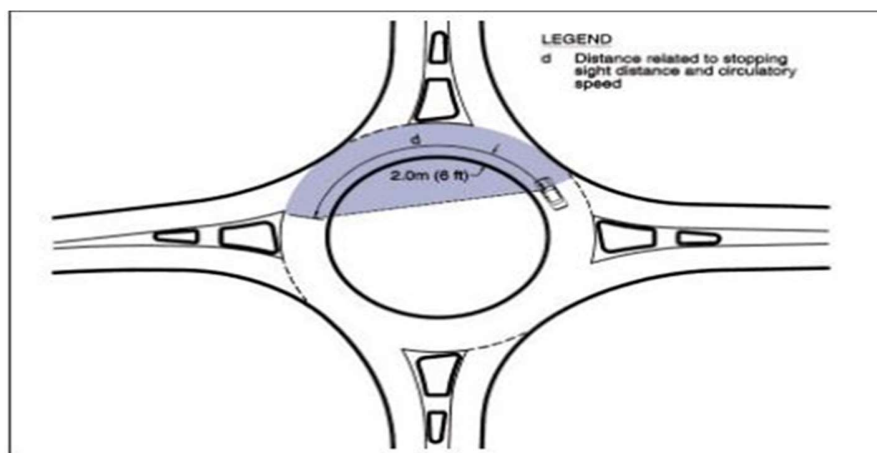


Figure 23: Circulatory sight distance (USDOT, 2017)

3.1.4 Formulation of Stopping sight distance

The stopping sight distance for US Department of Transportation is given by the equation 1 described below. The stopping sight distance should be measured using driver eye height of 1,080 mm (3.54 ft) and height of object of 600 mm (1.97 ft) in accordance with AASHTO “Green Book. The same stopping sight distance is used in approach sight distance, exit crosswalk sight distance and circulatory sight distance. The only difference observed is speed. For approach sight distance we will take entry speed of vehicle; for circulatory sight distance we will take circulatory speed. The interesting part is exit crosswalk sight distance in which case we take entry speed only because the exit speed is governed by the entering speed of vehicle.

Equation 1: Stopping Sight Distance (USDOT, 2017)

$$d = (0.278)(t)(V) + 0.039 \frac{V^2}{a} \quad (6-2a, \text{ metric})$$

where:

- d = stopping sight distance, m;
- t = perception-brake reaction time, assumed to be 2.5 s;
- V = initial speed, km/h; and
- a = driver deceleration, assumed to be 3.4 m/s².

3.2 Intersection Sight Distance in roundabouts

Intersection sight distance is the distance required for a vehicle that does not have the right of way to ensure that the driver can see and safely react to the conflicting vehicles. Intersection crashes are mainly caused due to inadequate sight distance at intersections. Therefore, building roundabouts instead of intersections reduces number of conflicting points, in conclusion reduces accident rates. However, providing adequate sight distance at roundabouts to manoeuvre the vehicle safely is considered an important factor.

For intersection sight distance, we provide a clear view of traffic for the entering vehicle to the circulating roadway to perceive and react to the acceptable gap. Intersection sight distance is calculated through the establishment of adequate sight lines that allows a driver to see and safely

react to the conflicting vehicles. The sight triangles also help drivers of conflicting vehicles to see the approaching vehicles.

The required sight distance in roundabouts is achieved through the same method which we applied in four-legged intersections i.e. the sight triangle method. The sight triangles are provided and checked at each entry. Intersection sight distance is a main part of establishing a safe roundabout. Meanwhile, it has been proved by the researchers that more intersection sight distance resulted in higher vehicle speed and thus by affecting the safety of the roundabout so close attention must be given to ensure that does not happen.

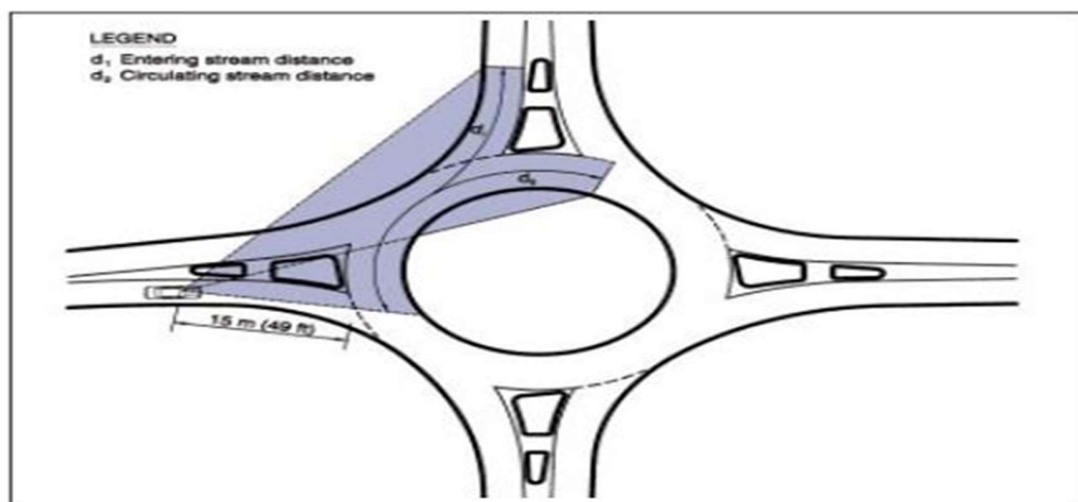


Figure 24: Intersection sight distance (USDOT, 2017)

3.2.1 Formulation of Intersection Sight Distance

Intersection sight distance should be measured using driver height of 1,080 mm (3.54 ft) and an object height of 1,080 mm (3.54 ft) as stated by AASHTO. The sight distance “triangle” has two conflicting approaches that must be checked independently. The first conflicting approach is the length of approach leg of sight triangle which should be limited to 15 m (49 ft). According to the USDOT guidelines it is necessary to restrict this sight distance to minimum requirements using landscaping. The second conflicting approach is when a vehicle approaching an entry to roundabout faces conflicting vehicles within the circulatory roadway. In this case the USDOT have

given an empirical formula which gives us the length of conflicting leg of sight triangle for a given design speed. Sight distance at roundabouts is derived for two cases. The first one is entering stream, it comprises of vehicles from the immediate upstream entry. The speed for this movement can be approximated by taking the average of the entry path speed (path with radius R_1) as shown in below diagram and the circulating path speed (path with radius R_2). The second is circulating stream, it comprises of vehicles that entered the roundabout prior to the immediate upstream entry. This speed can be approximated by taking the speed of left turning vehicles (path with route having radius R_4).

Equation 2: Intersection Sight Distance (USDOT, 2017)

$$b = 0.278(V_{major})(t_c) \quad (6-3a, \text{ metric})$$

where: b = length of conflicting leg of sight triangle, m
 V_{major} = design speed of conflicting movement, km/h, discussed below
 t_c = critical gap for entering the major road, s, equal to 6.5 s

Entering stream=0.5 (the entry path speed (path with radius R_1 + circulating path speed (path with radius R_2))

Circulating Stream = speed of left turning vehicles (path with radius R_4)

The critical gap i.e. 6.5 seconds is based on the total time required for a passenger car to turn right while requiring the conflicting stream vehicle to slow no less than 70 percent of initial speed. Passenger cars are assumed to be as critical design vehicle for intersection sight distance. Furthermore 6.5 sec is also valid for single-unit and combination truck speeds that are at least 10 km/h and 15 to 20 km/h slower than passenger cars. The formula for conflicting approach has been applied for different speeds and is formulated into a given table below:

Table 4: Conflicting approach speed and its corresponding distances

Conflicting Approach Speed (km/h)	Computed Distance (m)
20	36.1
25	45.2
30	54.2
35	63.2
40	72.3

Conflicting Approach Speed (mph)	Computed Distance (ft)
10	95.4
15	143.0
20	190.1
25	238.6
30	286.3

It is advisable to provide no more than the minimum required intersection sight distance on each approach. Excessive intersection sight distance can lead to higher vehicle speeds that reduce the safety of the intersection for all road uses. The height of Central Island and other landscaping techniques control the intersection sight distance.

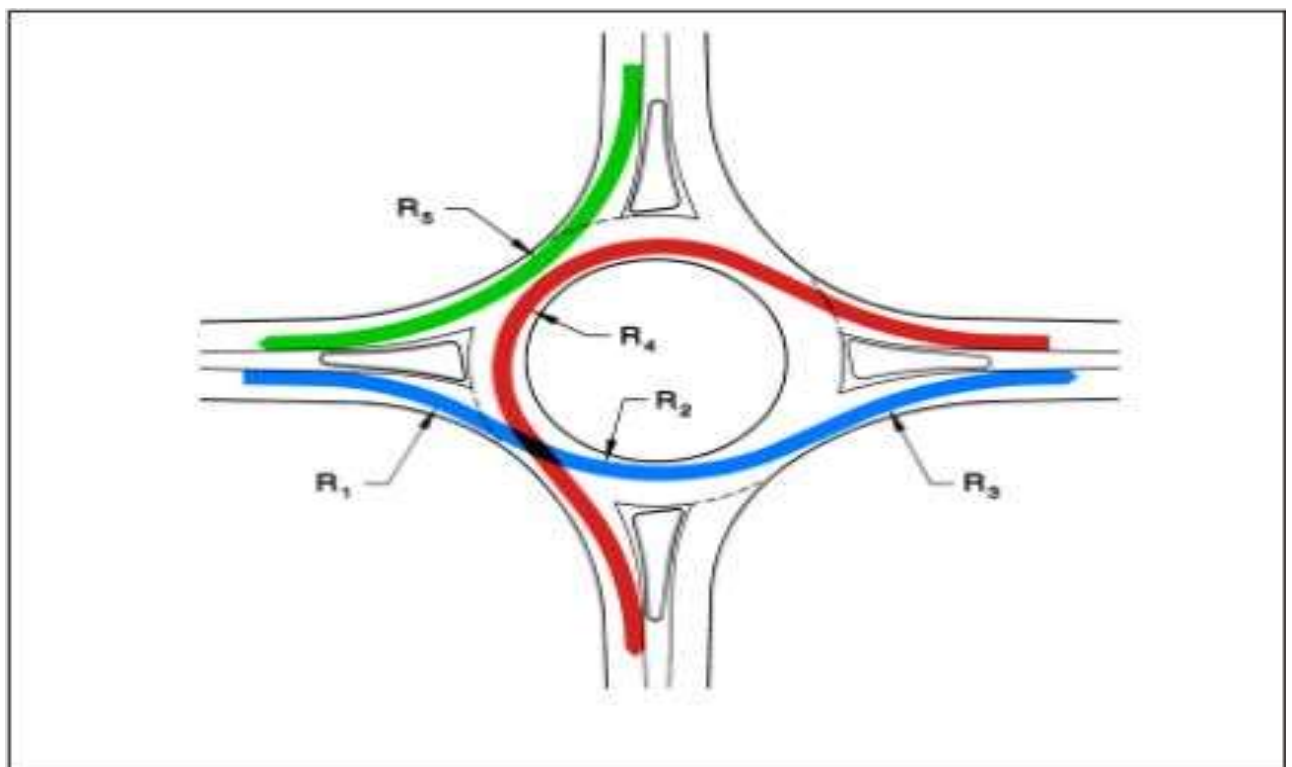


Figure 25 : Intersection sight distance on roundabouts in USDOT

3.3 Intersection Sight Distance at Turbo Roundabouts (Graphical Representation)

At turbo roundabouts when we plot the sight distance, it comes same as in modern lane roundabouts. Sight-lines are drawn from approaching vehicle at approach leg to the entering and circulating vehicle. During my research I drew sight-line in AutoCAD using the add-on software called “Torus”. In the below figures i.e. figure 26, the paper is showing the Intersection sight distance at turbo roundabouts from “AutoCAD”. In fig 26 the red and white hatched portion is the truck apron and yellow shaded portion shows the raised mountable divider. Vehicle is shown at different approaches; the light blue lines emerging from the vehicle are the sight lines for intersection sight distance. The dashed pink line shows the vehicle path movement of entering conflicting vehicle and circulating conflicting vehicle. Sight lines are drawn to a point, where distance is measured from conflict point as starting point, the equation for that stopping sight distance is given by equation 2. At Approach 1 and Approach 2 simple sight-lines are formed just like in the modern roundabouts, but at Approach 3 and Approach 4 sight lines are formed are little bit different. The sight-lines at approach 3 and approach 4 have two sight-lines for both circulatory and entering vehicle; the reason behind this is there are two conflicting vehicles which are going to crash with entering vehicle. Out of these two sightlines the sightline that is selected for design purpose is the one that covers more area; for example, at approach 3 and approach 4 the outer entering lane covers up more area hence that sight-line is selected. In case of circulating vehicle outer circulatory vehicle sightline covers more area in case of approach 3 while inner circulatory vehicle sight-line is selected as guiding sightline in case of approach 4. The approach 2 and approach 1 do not have two sight-lines because in approach 1 there is a bypass lane due to which vehicle entering from approach 2 and going right does not conflict whereas when approach vehicle is at approach 2, the entering vehicle surpasses and do not conflict due to raised mountable dividers.

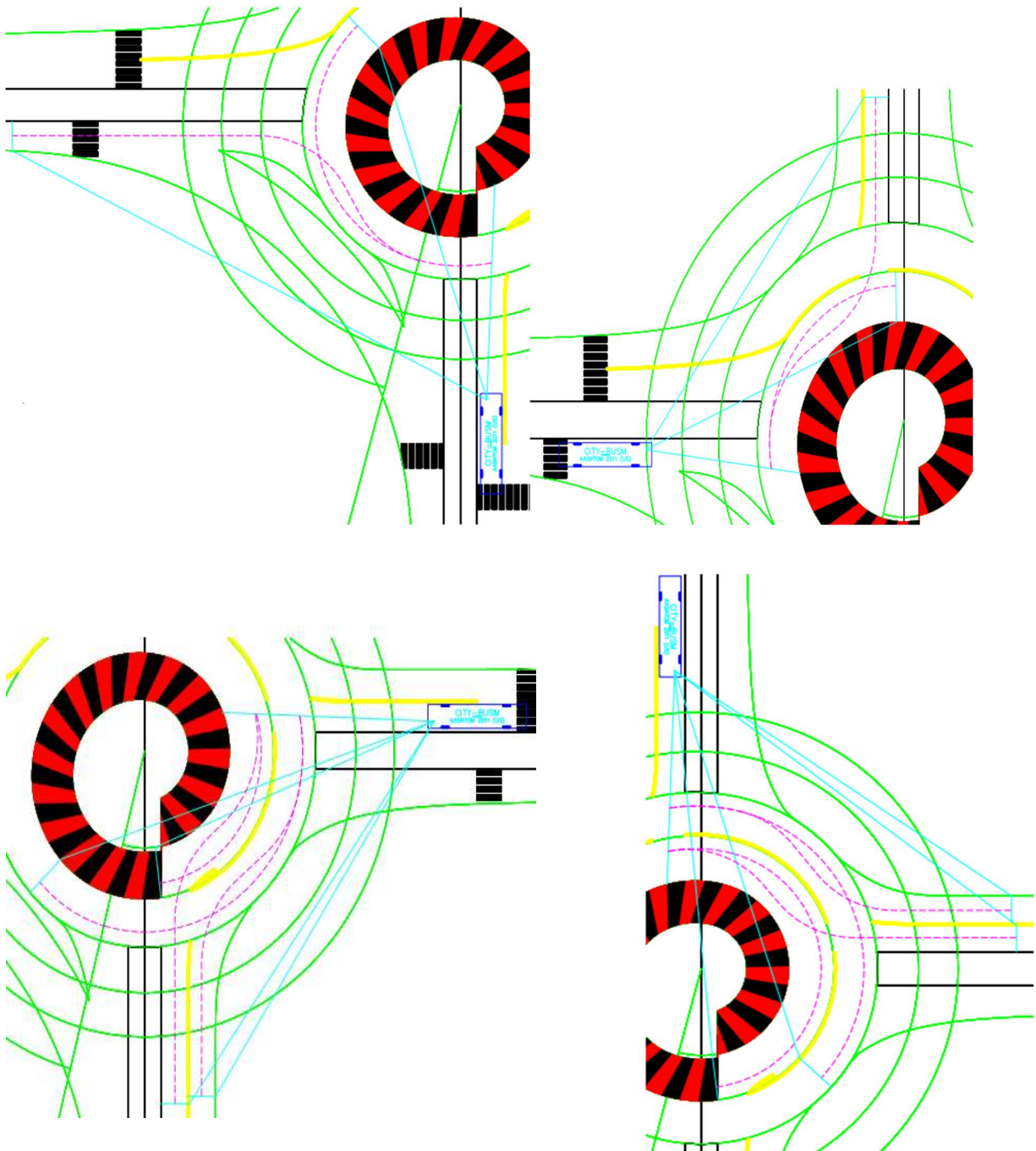


Figure 26: Sight Distances at all approaches. Approach 1, Approach 2, Approach 3, Approach 4 clockwise

4.0 Analytical Approach to Intersection Sight Distance

As previously discussed in intersection sight distance we provide entering vehicles a clear view of traffic on the circulating roadway to perceive and react to an acceptable gap. Intersection sight distance is achieved through the establishment of adequate sight lines that allow a driver to see and safely react to potentially conflicting vehicles. As done in article 3.3; ISD can be plotted and found out by graphical method and that has been the conventional method. An analytical model is developed in this paper in next few articles using coordinate geometry and mathematical equations. Similar type of analytical models were developed for clearance needs with similar type of methods for vehicles at different types of intersections; for example (Ali et al., 2009; Easa and Ali, 2006; Easa et al., 2004; McCoy et al., 2001; Joshua and Saka, 1992) and for pedestrians at railway crossings (Easa et al. 2017), Design guideline for symmetrical single lane roundabout based on Intersection sight distance (Said M. Easa, 2017). According to (Džambas et al., 2017) the driver has to see both conflicting vehicles i.e. circulating and entering vehicles from the left quadrant. The visibility distance for circulating vehicles is based on 5 sec gap and we will consider the same 5 sec gap for turbo-roundabout. According to the Australian guidelines (Austroads 2009) the visibility depends on the Inscribed circle diameter.

The (USDOT, 2017) suggests checking the sight distance L_{min} (15 m) from the yield line, but (Said M. Easa, 2017) argue to check the sight distance at yield line too. Similar to (Said M. Easa, 2017) suggestion Australian guidelines also check sight distance visibility at both these locations i.e. at yield line and at 15m from yield line (Akçelik, 2014).

4.1 Methodology

The procedure behind developing these equations for any type of turbo roundabout involves certain processes. These different processes are here summarised in a form of method through which anyone can develop these analytical equations. The steps are:-

1. Develop a turbo block outline with one primary translation axis for a central island of random radius.

2. Analyse the swept paths of the design vehicle along different route i.e. while the vehicle is circulating and whilst vehicle is entering at an entry radius.
3. Using the swept path determine the central island radius and type of turbo roundabout and design the turbo block.
4. Repeat the procedure if needed for different design vehicles.
5. After your turbo roundabout is determined the first step towards analysing ISD (Intersection Sight Distance) is finding the coordinates of centre of the arcs on the left-hand side and right-hand side of the translation axis. The coordinates for right hand side semicircles are assumed to be at origin.
6. After we have determined the centre of semicircles on both sides of translation axis, the next step would be finding the coordinates of approach vehicle. The first case will be when approach vehicle will be at L_{min} (15 m) distance from yield line.
7. Finding coordinates of conflict point is the next step. Determination of coordinates of conflict point is very important because, the coordinates of this point can help us to determine the coordinates of conflicting circulating and conflicting entering vehicles. The scope of this study is limited to only conflicting circulating vehicles, so paper will focus on just that.
8. Using equation 2 position of circulating vehicle is determined and simultaneously its coordinates are determined.
9. Using the coordinates of approach vehicle and coordinates of circulating vehicle, an equation for clearance is developed which changes with the circulating speed i.e. V_c .
10. For the second case when approach vehicle is at yield line, we first find coordinates of approach vehicle like step 6.
11. The coordinates of conflict point remain same as it conflicts point does not change.
12. Now repeat the steps 8 and 9 i.e. coordinates of circulating vehicles are determined.
13. To find maximum clearance use the equation developed in step 9 and optimize it between the suitable limits.

4.2 Assumptions

The following assumptions were made while developing the analytical model-:

1. The centre for arcs on the right-hand side is at origin.
2. The approach legs are intersecting the turbo roundabout at 90-degree angle.
3. The t_c for intersection sight distance is 5 sec.
4. Distance from the front end and driver's eye distance is assumed to be 2.43 m or 7.97 feet.
5. For simplicity of the study we either put turbo roundabout upside down on traditional Cartesian coordinate system or arrange coordinate system upside down (Fig 27).

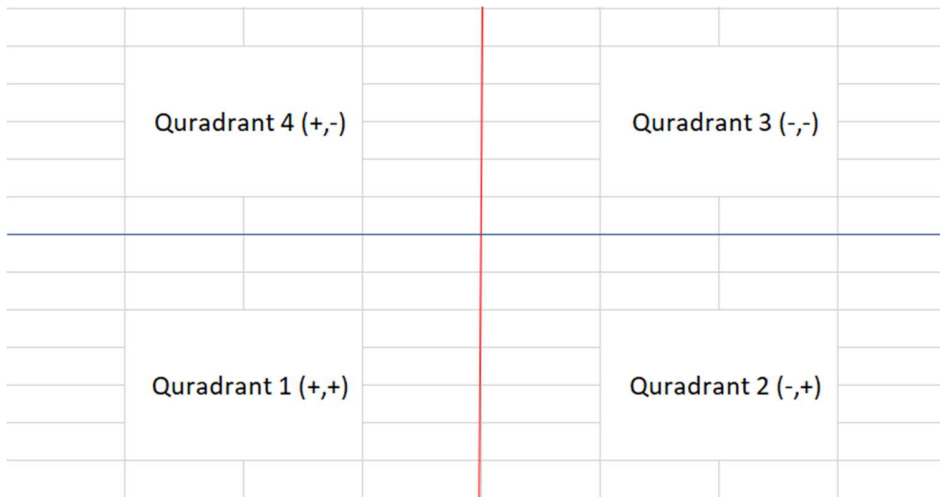


Figure 27: Assumption 4

4.3 Development of turbo block

In our case we have taken knee type roundabout with a 10.50 m radius with a primary translation axis at 15 degrees or θ_T . Although (Murphy & Manager, 2015) suggests that the translation axis angle should depend on the swept of the vehicle and should be an iterative process but using the current fleet of large vehicles 15 degrees has somewhat become a constant in all the turbo blocks. Relation between different radii of turbo-block has been derived during further discussion below: The procedure of transitioning from turbo-block to turbo roundabout consists of adding a truck-apron and adding approach legs. By constructing the width of apron according to Dutch guideline

a shift is observed between inner and outer truck apron. This shift is observed to be 5cm and is denoted by a constant “f” (Džambas et al., 2017). The width of a circulatory roadway is denoted by “W_c”. The initial radius is the outer radius of the truck apron and the inner radius of inner circulatory lane. In all the given templates of turbo block the inner radius value is given i.e. “R₁” is given and we can choose the width of circulatory roadway depending on the swept path of the vehicle (T CROW,2008).

Using these values of “R₁”, W_c” and “f” we can develop the radius for other circles. To develop the radius of other circles we will use the relation

$$(D_2 - D_1 = W_c + f) \quad (3)$$

Where, “D” is the diameter of a specific semicircle. On closely observing the turbo-block we noted that it has many different semi-circles but only two centres; one is for all the semi-circles on right hand side of the translation axis and one for all the semi-circles on right hand side of the translation axis which can be clearly shown in the fig (28). The difference between the two centres when measured is approximately equal to half of the circulatory roadway width i.e. “W_c/2”. For an initial radius of “R₁” 10.50m, the other radius using the relation above equation 3 are formatted in form of below table.

Table 5:Different radius of turbo block

R ₁	10.50 m
R ₂	13.29 m
R ₃	16.08 m
R ₄	18.87 m
R ₅	21.66 m

After laying the turbo-block approach legs are added on each side of the turbo block to carve into a turbo-roundabout. The approach legs are then added at an exactly 90-degree angle along the roundabout as suggested by (Džambas et al., 2017).

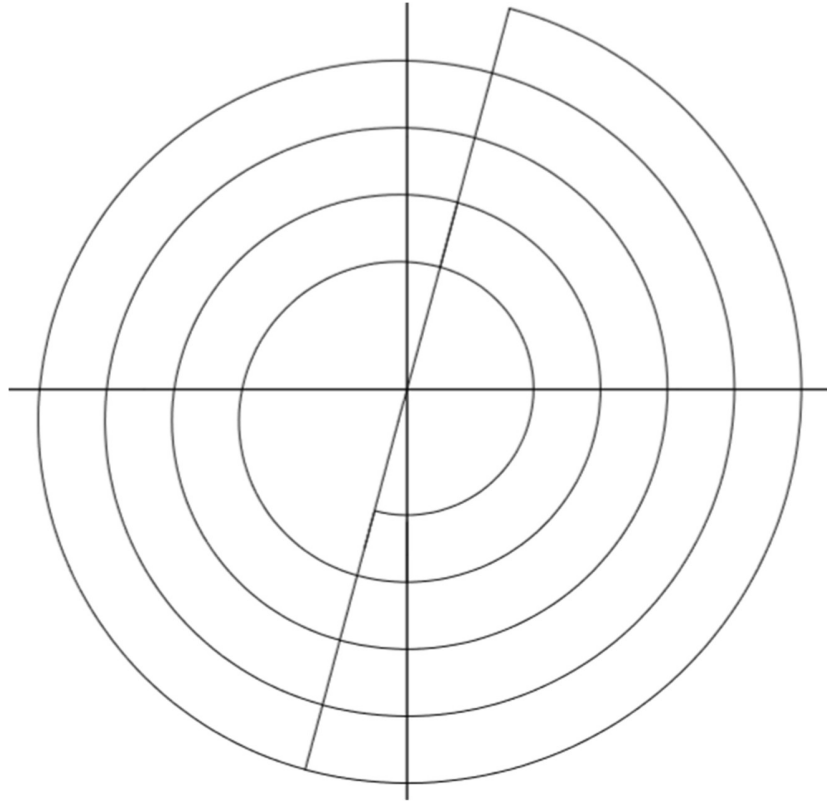


Figure 28: Generation of Turbo block

4.4 Coordinates of Significant points

4.4.1 Coordinates of New Centre

The new centre which is at $0.5W_C$ distance from the origin i.e. O_1 along the translation axis is named as “n” with coordinates as (X_n, Y_n) . Referring to fig 28 we know θ_T and distance W_c . The value of new coordinates will remain unchanged for all cases. Using the tools of trigonometry, the coordinates of new centre with respect to origin can be found out as follows -:

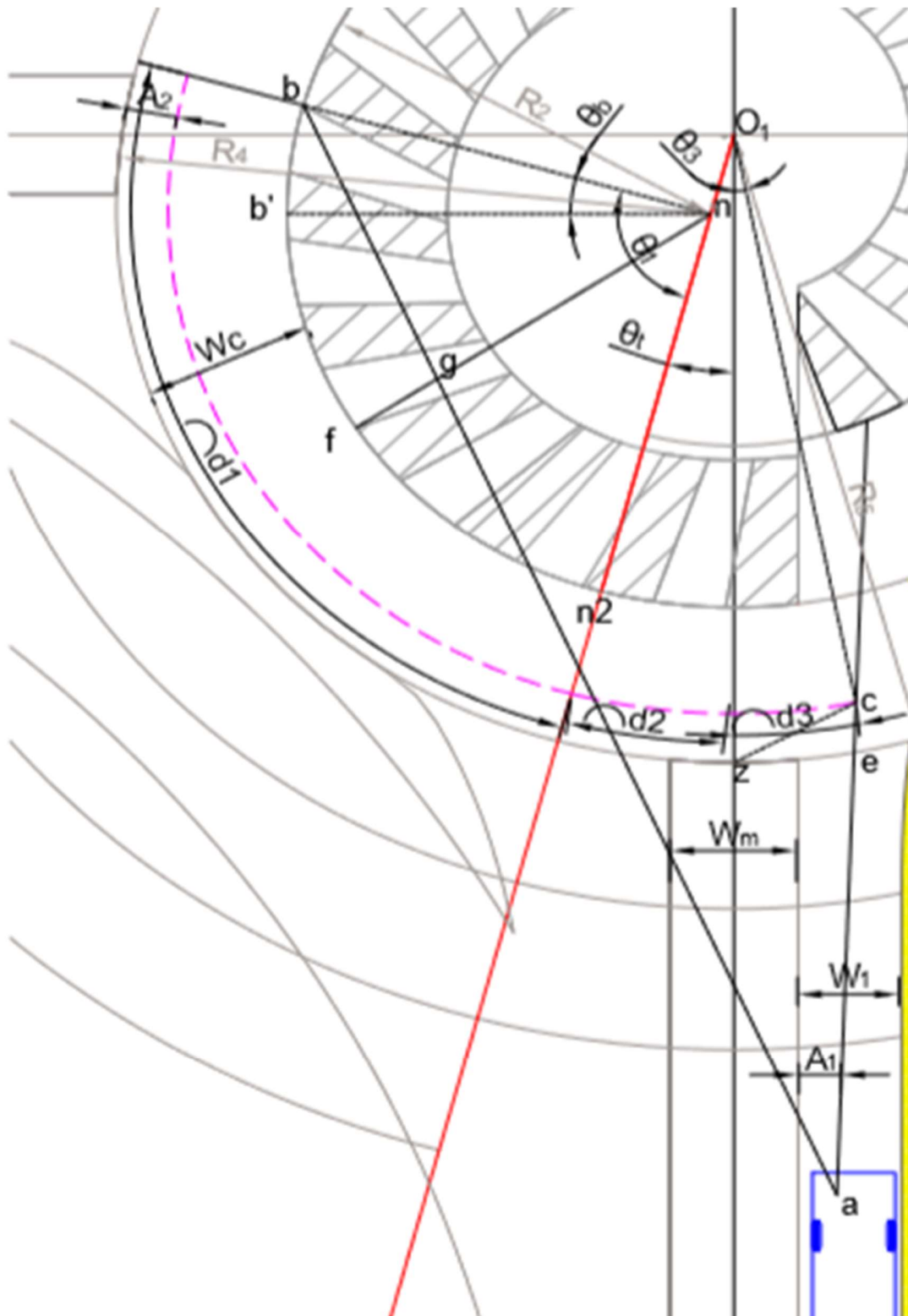


Figure 29: Significant points at turbo roundabout

Now “n” is new centre,

Its coordinates are found from right angle triangle O_1nn_1

$$\begin{aligned} x_n &= (O_1n)\sin\theta_T \\ &= \frac{W_c}{2}\sin\theta_T \end{aligned}$$

$$\begin{aligned} y_n &= (O_1n)\cos\theta_T \\ &= \frac{W_c}{2}\cos\theta_T \end{aligned}$$

4.4.2 Case -1 (Approach vehicle 15 m before yield line)

Following the standards set by (USDOT, 2017),(Said M. Easa, 2017) we first measure the sight distance at 15m (L_{min}) from yield line. The driver eye at 15 m from yield line is named as point “a” i.e. position of approach vehicle. From this point the vehicle will move towards the centre of the entry lane “W1” so that it can comfortably take turns either to circulatory lane “Wc”. This centre of the lane is named as “e”. There is median separating the entry and exit lanes; and the centre of the median when intersects with R_5 the point is named as “z”. The width of the median is named as “ W_m ”, Interestingly the nature of turbo roundabout is such as that the Y axis exactly passes through the centre off the median. The difference between the driver eye and edge of circulatory roadway is “ A_2 ” and difference between the driver eye and outer edge of median is “ A_1 ”. From fig (29) we take R_5 i.e. radius of inscribed circle diameter with the centre as origin.

Coordinates of Approach Vehicle

$$x_a = \frac{W_m}{2} + W_1 - A_1 \quad (4)$$

$$y_a = R_5 + L_{min} \quad (5)$$

Coordinates of Conflict Point

To find the coordinates of conflict point we first must find coordinates of point “e” i.e. x_e, y_e

$$x_e = \left(\frac{W_m}{2} + \frac{W_1}{2} \right) \quad (6)$$

$$y_e = \sqrt{R_5^2 - \left(\frac{W_m}{2} + \frac{W_1}{2} \right)^2} \quad (7)$$

$$\text{Or } \left(R_5^2 - \left(\frac{W_m}{2} + \frac{W_1}{2} \right)^2 \right)^{0.5}$$

Now to find coordinates of point C,

Let coordinates be x_c, y_c

As point 'c' lies on extension of line 'ae' and both 'ae' and 'ac' must have same slopes therefore equation of line 'ac' with x_c & y_c satisfying it is as follows:

$$x_c = x_a + \frac{(y_c - y_a)}{P_{ac}} \quad (8)$$

$$\text{Where } P_{ac} = \frac{y_e - y_a}{x_e - x_a}$$

Here P_{ac} is slope of line 'ac' or 'ae'.

Now in order to find coordinates of point 'c' we see that circle of radius R_5 intersects the line 'ac' at 'c'.

Equation of circle with center as $O_1(0,0)$ and radius R_5 with x_c & y_c satisfying it is

$$x_c^2 + y_c^2 = (R_5 - A_2)^2 \quad (9)$$

Therefore, their point of intersection x_c & y_c is found out as follows:

Putting $x_c = x_a + \frac{(y_c - y_a)}{P_{ac}}$ i.e. putting equation (8) into equation (9).

$$(x_a)^2 + \frac{(y_c - y_a)^2}{P_{ac}^2} + \frac{2x_a(y_c - y_a)}{P_{ac}} + y_c^2 = (R_5 - A_2)^2$$

Converting it into quadratic form for solution of y_c

$$(x_a)^2 + \frac{y_c^2}{P_{ac}^2} + \frac{y_a^2}{P_{ac}^2} - \frac{2y_c y_a}{P_{ac}^2} + \frac{2x_a(y_c - y_a)}{P_{ac}} + y_c^2 = (R_5 - A_2)^2$$

$$y_c^2 \left[\frac{1}{P_{ac}^2} + 1 \right] + y_c \left[\frac{-2y_a}{P_{ac}^2} + \frac{2x_a}{P_{ac}} \right] + \left[\frac{y_a^2}{P_{ac}^2} - \frac{2x_a y_a}{P_{ac}} - (R_5 - A_2)^2 \right] = 0 \quad (10)$$

Thus, this is quadratic equation in y_c i.e.

$$ay_c^2 + by_c + c = 0$$

Where

$$a = \left[\frac{1}{P_{ac}^2} + 1 \right]$$

$$b = \left[\frac{-2y_a}{P_{ac}^2} + \frac{2x_a}{P_{ac}} \right]$$

$$c = \left[\frac{y_a^2}{P_{ac}^2} - \frac{2x_a y_a}{P_{ac}} - (R_5 - A_2)^2 \right]$$

Solving values for “a”, “b”, “c” and substituting in solution of quadratic equation

$$y_c = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (11)$$

we can find y_c , This gives us two values. It is important to take care that we are interested in only those values which correspond to quadrant in which conflict point lies.

substituting values of y_c in equation 9,

$$x_c^2 + y_c^2 = (R_5 - A_2)^2 \text{ or } x_c = \{(R_5 - A_2)^2 - y_c^2\}^{0.5} \quad (12)$$

Thus, we can find x_c i.e. equation 12.

Coordinates of Circulating Vehicle

To find the coordinates of circulating vehicle, we first need to locate position of circulating vehicle for which we will use equation 2. From equation 2 we will get the total distance ‘d’ travelled by the vehicle in ‘ t_c ’ seconds. The total ‘d’ can be divided into three parts i.e. ‘ d_1 ’, ‘ d_2 ’, ‘ d_3 ’ depicted in figure (29). ‘ d_3 ’ distance covered by vehicle between point ‘c’ and ‘z’ and make an angle of θ_3 . The ‘ d_2 ’ is the distance covered along arc subtended by the angle θ_T and ‘ d_3 ’ is the rest of the distance which can be found out by subtracting ‘($d_1 + d_2$)’ from total distance ‘d’.

$$\text{Total travelling distance} = d = d_1 + d_2 + d_3 = 0.278V_c t_c$$

The target is to find coordinate of point b and for this θ_b is required to be found.

For this angle $b'nn_2 = 90^\circ - \theta_T$, where 90 is in degrees it can also be represented as radians as done in application example

$$\text{and } \theta_b = \theta_1 - \text{angle } b'nn_2$$

$$= \theta_1 - (90 - \theta_T)$$

Hence,

$$\theta_b = \frac{d_1}{(R_4 - A_2)} - (90 - \theta_T) \quad (13)$$

As we have already discussed d_1 can be found as follows:

$$d_1 = d - (d_2 + d_3) \quad (14)$$

$$d_2 = \theta_T \times (R_5 - A_2) \quad (15)$$

$$\& \quad d_3 = \theta_3 \times (R_5 - A_2) \quad (16)$$

We need to find θ_3 for knowing d_3 see figure (29)

Join 'c' & 'z'. Now in triangle O_1cz

$$O_1c = R_5 - A_2$$

$$O_1z = R_5$$

$$zc = \text{distance between coordinate of } z \& c = \sqrt{(x_z - x_c)^2 + (y_z - y_c)^2} \quad (17)$$

Coordinates of z are

$$x_z = 0$$

$$y_z = R_5$$

Coordinates of 'c' can be had from the value of x_c & y_c from solution of equation 11 & 12

Filling these values in equation (17) 'zc' can be found.

Now

In triangle O_1cz

$$\cos\theta_3 = \frac{(R_5 - A_2)^2 + R_5^2 - (zc)^2}{2(R_5 - A_2)R_5} \quad (18)$$

$$\text{or } \theta_3 = \cos^{-1} \left[\frac{(R_5 - A_2)^2 + R_5^2 - (zc)^2}{2(R_5 - A_2)R_5} \right]$$

Then $d_3 = \theta_3 \times (R_5 - A_2)$ & $d_2 = \theta_T \times (R_5 - A_2)$

& d_1 can be known as

$$d_1 = d - (d_2 + d_3)$$

After finding d_1 , substitute the value of d_1 in equation (12)

$$\theta_b = \frac{d_1}{(R_4 - A_2)} - (90 - \theta_T); \theta_b \text{ can be found out.}$$

Thus, coordinates of b

$$x_b = (R_2)\cos\theta_b + \frac{W_c}{2}\sin\theta_T \quad (19)$$

$$y_b = -(R_2)\sin\theta_b + \frac{W_c}{2}\cos\theta_T \quad (20)$$

4.4.3 Case 2 (Approach Vehicle at yield line)

For case 2 as mentioned in methodology only the coordinates of approach vehicle changes, the rest of the equations remain same. The equations for coordinates of conflict point and the coordinates of circulating vehicle does not change as they are independent of the coordinate value of approach vehicle. The parameter that will vary will be clearance and maximum clearance. As the front end of the vehicle will approach yield line, there will be certain distance from the front end and driver's eye. As stated in assumptions this distance is assumed to be 2.43m or 7.97 feet. The coordinates of approach vehicle will be -:

$$x_a = \left(\frac{w_m}{2} + \frac{w_1}{2} \right) \quad (21)$$

$$y_a = R_5 + 7.97 \text{ feet} \quad (22)$$

4.5 Guideline for Lateral Clearance

Lateral Clearance is the distance required without any sight obstruction so that approach vehicle can see the possible conflict vehicle. the total area covered under this distance is known as clear zone ; in fig(24) light blue shaded zone implies clear zone.(USDOT, 2017) recommended that we should not provide more than required clearance otherwise it can lead to higher crash frequency. To control the required or maximum clearance, (Said M. Easa, 2017) recommends planting trees or fence or any kind of landscape technique which can act as a guideline for sight line. Also(USDOT, 2017) give us restriction over height of central island and landscaping on central island in the clear zone. Although outside of clear zone higher landscaping increase safety as it impacts psychologically to drivers to reduce the vehicle speed.

4.5.1 Defining Clearance

The formulation of lateral clearance depends on the coordinates of the approach and the circulating conflicting vehicles both of which can be found out by equations 19,20,4,5. Considering an arbitrary Point f on the edge of the truck apron (x_f, y_f) , a point “g” is determined where line “ab”

intersects “nf”. Now that the points are set, we can establish that the lateral clearance is equal to distance “gf”.

Slope of line ‘nf’ is

$$P_{nf} = \frac{y_f - y_n}{x_f - x_n}$$

and equation of line *nf* is:-

$$y = y_n + P_{nf}(x - x_n) \quad (23)$$

$$y = \frac{y_f - y_n}{x_f - x_n}(x - x_n) + y_n \quad (24)$$

Similarly Slope of line ‘ab’ is

$$P_{ab} = \frac{y_b - y_a}{x_b - x_a} \text{ and e}$$

equation of line ‘ab’ is:-

$$y = y_a + P_{ab}(x - x_a) \quad (25)$$

$$y = y_a + \left(\frac{y_b - y_a}{x_b - x_a} \right) \times (x - x_a) \quad (26)$$

Lines having equations at (24) & (26) intersect at unique point ‘g’ the coordinates of which can be found out by simultaneously solving these equations

So equating Eq (24) and Eq (26) (x,y can be found which gives values of x_g, y_g),

$$\text{Therefore, } y_n + P_{nf}(x_g - x_n) = y_a + P_{ab}(x_g - x_a)$$

$$x_g(P_{nf} - P_{ab}) = x_n P_{ab} + x_n P_{nf} + y_a - y_n$$

$$\text{Or } x_g = \frac{y_a - y_n - x_n P_{ab} + x_n P_{nf}}{P_{nf} - P_{ab}} \quad (27)$$

Putting value of eq (27) into eq (24)

$$y_g = y_n + P_{nf}(x_g - x_n)$$

$$y_g = y_n + P_{nf} \left[\left(\frac{y_a - y_n - x_n P_{ab} + x_n P_{nf}}{P_{nf} - P_{ab}} \right) - x_n \right]$$

$$y_g = y_n + \frac{P_{nf}}{P_{nf} - P_{ab}} [y_a - y_n - x_n P_{ab} + x_n P_{nf} - x_n P_{nf} + x_n P_{ab}]$$

$$y_g = \frac{y_a P_{nf} - y_n P_{ab} - (x_a - x_n) P_{nf} P_{ab}}{P_{nf} - P_{ab}} \quad (28)$$

Therefore, for finding clearance we put value from equation 27 and equation 28 into equation 29 we get lateral clearance at a point “f”.

$$C_f = \text{Lateral Clearance} = gf = (R_2) - \sqrt{(x_g - x_n)^2 + (y_g - y_n)^2} \quad (29)$$

4.5.2 Maximum Clearance

Note that “f” point is variable and the coordinate value of point “g” depends on coordinate value of “f”. To find the maximum clearance i.e. $C_{f(\text{MAX})}$ we need to locate point “f” multiple time and evaluate the maximum clearance. As doing this task manually is a challenge, the study used excel add in tool called “Solver”. In solver we optimize the maximum clearance within the upper and lower limits.

The following charts try to show the maximum clearance at different radius and different circulating speeds which are found by the excel tool “Solver”. Excel *Solver* uses simple optimization model

$$\text{Maximize } Z = C_f \quad (30)$$

Subject to

$$d_L < d_f < d_U \quad (31)$$

where d_f = distance of Point f on the edge of truck apron (decision variable), d_L and d_U = arbitrary lower and upper limits of the decision variable, that cover possible range of lateral clearance.

4.5.3 Design Aids

Using equation 30 and 31, table 7 and table 8 are formulated where for different circulating speeds maximum clearance is found out for radius 10.50 m and radius 12 m. Then the fig 30 and fig 31 shows the relation between circulating vehicle speed and maximum clearance. As shown in both the graphs; for any radius the clearance increases with the circulating speed. The slope obtained for both radius and both the cases are nonlinear functions although clearance obtained; when vehicle is at yield line is more in contrast to vehicle is 15m before yield line for both any radius. Bar chart 32 reinforce the above two stated facts i.e. as circulating speed increases, clearance

increases, and clearance is also more when vehicle is at yield line is in contrast to vehicle is 15m before yield line. The bar chart 32 also shows the fact that despite any speed, larger the radius less will be the clearance for both cases.

The findings obtained from this graph were similar to that found by (Said M. Easa, 2017) where in case of multi-lane symmetrical roundabout the maximum clearance at yield line were larger and maximum clearance at larger radius roundabouts were less.

Table 6: Maximum Clearance at variable speeds for radius 10.50 m

RADIUS 10.50 OR 34.45					
		AT 15m below yeild line		At yield line	
VC(MPH)	VC(KM/HR)	Clearance(ft)	Clearnce(m)	Clearance(ft)	Clearnce(m)
10	16.094	0.0155	0.0047244	1.819	0.5544312
13	20.9222	3.1901	0.97234248	7.3219	2.2317151
15	24.141	7.6602	2.33482896	12.2809	3.7432183
17	27.3598	13.4482	4.09901136	17.9793	5.4800906
19	30.5786	20.2069	6.15906312	24.23	7.385304
21	33.7974	27.6549	8.42921352	30.8971	9.4174361
23	37.0162	35.5468	10.8346646	37.8146	11.52589

Table 7: Maximum Clearance at variable speeds for radius 12 m

RADIUS 12m OR 39.37 feet					
		AT 15m below yeild line		At yield line	
VC(MPH)	VC(KM/HR)	Clearance(ft)	Clearnce(m)	Clearance(ft)	Clearnce(m)
10	16.094	0	0	1.3325	0.406146
13	20.9222	2.175	0.66294	6.2667	1.9100902
15	24.141	6.0231	1.83584088	10.8674	3.3123835
17	27.3598	11.2454	3.42759792	16.234	4.9481232
19	30.5786	17.5087	5.33665176	22.195	6.765036
21	33.7974	24.5527	7.48366296	28.6284	8.7259363
23	37.0162	32.1585	9.8019108	35.3954	10.788518

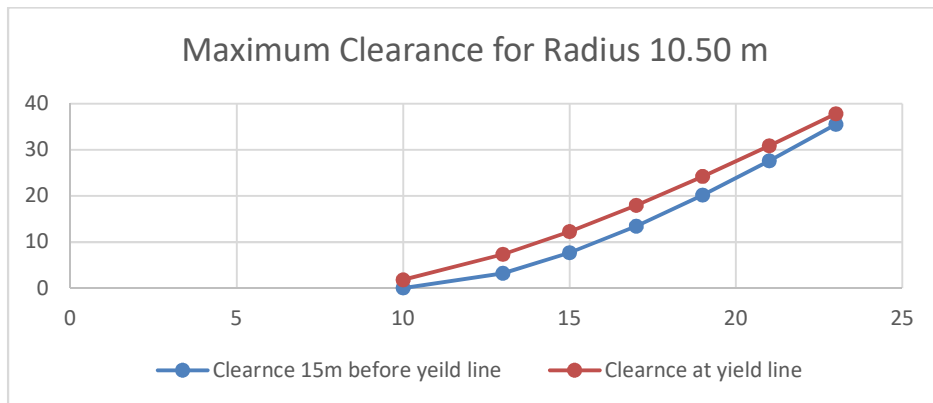


Figure 30: Graphical representation of clearance at different speeds for radius 10.50 m

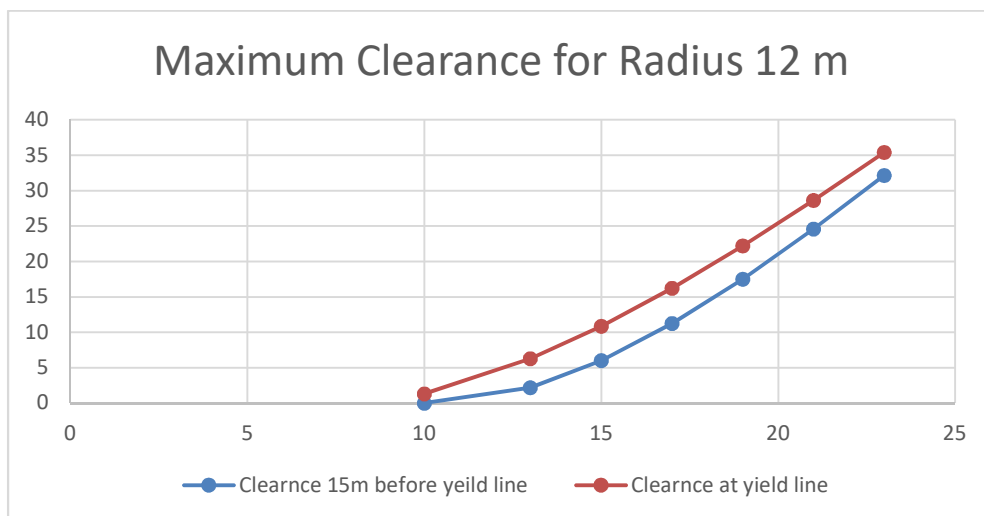


Figure 31: Graphical representation of clearance at different speeds for radius 12 m

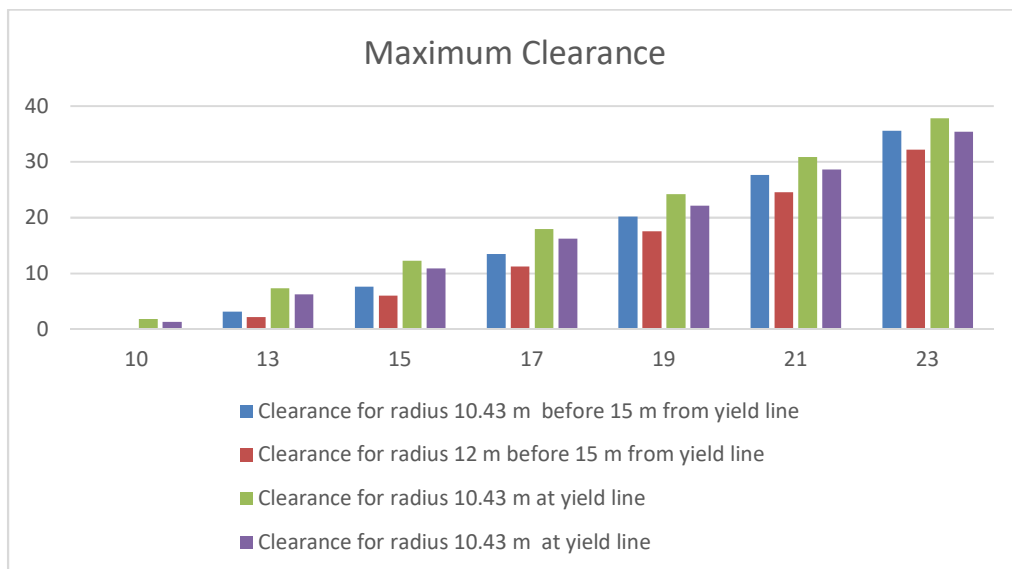


Figure 32: Bar chart depicting clearance value for all cases

5.0 Application Example

Question -: Consider a multi-lane turbo roundabout with initial radius i.e. $R_1 = 10.50$ m or 34.45 feet, $V_{cir} = 16$ mph, and $W_1 = 10.46$ feet, and $W_c = 16.9$ feet. The primary translation axis is at 15 degrees or 0.2618 radians with y axis. The width of the median is $W_m = 13.1234$ feet and $t_{critical} = 5$ sec. Determine the required maximum lateral clearance on the edge of truck apron for both the cases a) when vehicle is 15 m before yield line b) when vehicle is at yield line?.

Solution-: For both the cases the input or given data is same is the same, table 7 shows all the given data.

Table 8: Given data for application example

INPUT		
Parameter	Value	units
X_0	0	feet
Y_0	0	feet
R_1	34.45	feet
W_1	10.46	feet
f	1.42	feet
W_M	13.12	feet
W_C	16.90	feet
A_1	6.56	feet
A_2	5.85	feet
L_{MIN}	49	feet
θ_t	0.26	radians
t_c	5	sec
V_c	16	mph
X_f	42	feet
Y_f	26	feet

Before finding all the significant coordinates of the points we first need to find all other radius of turbo roundabout. As mentioned in article 4.3 ($R_2 - R_1 = ((W_c + f)/2)$) is used to find all other radius of turbo roundabout. It is an iterative process where after finding R_2 , we can find R_3 using equation ($R_3 - R_2 = ((W_c + f)/2)$) and similarly R_4 and R_5 can be found out. Table 8 shows the result of all other radius which are found using initial radius i.e. R_1 .

Table 9: Output Radius of all other sides of translation axis

OUTPUT RADIUS		
Parameter	values	units
R_2	43.61	feet
R_3	52.77	feet
R_4	61.93	feet
R_5	71.09	feet

Solution a) Case -1 (Vehicle at 15m before yield line)

For the vehicle 15m or 49ft below yield line i.e. L_{min} after finding all radius; first the centres of semicircles on both sides of translation axis is determined after which other coordinates of significant points are determined. Table 9 shows all the coordinates of the point and will also validate graphically through AutoCAD in further section.

Table 10: Coordinates of significant points for vehicle at 15m before yield line

Coordinates of significant points	X-Ordinate (in feet)	Y-Ordinate (in feet)
Coordinates of new center	$X_n = 2.18$	$Y_n = 8.16$
Coordinates of approach vehicle (Equation 4 and 5)	$X_a = -10.47$	$Y_a = 120.09$
Coordinates of point "e" (Equation 6 and 7)	$X_e = -11.84$	$Y_e = 70.09$
Coordinates of conflict point (Equation 11 and 12)	$X_c = 11.97$	$Y_c = -65.35$
Total Distance travelled from conflict point ($0.278 * V_c * t_c$) = 117.42 ft or 35.79 m		
Coordinates of circulating conflicting vehicle (Equation 19 and 20)	$X_b = 44.13$	$Y_b = -3.75$
Clearance (Equation 29)	10.029 (The value of which depends on X_g and Y_g , which further depend on value of X_f and Y_f which are input values)	

The following table shows the output numerical values received after inputting the given value in equations mentioned in chapter 4. The table clearly depicts the equation number used in calculating that particular value.

Solution b) Case -2 (Vehicle is at yield line)

For the second case we know that coordinate values of conflict point “c” and circulating vehicle point i.e. “b” remain constant. As shown in table 10 the values obtained for point “b”, “c” and “e” are same as obtained in table 9. The value of point “a” changes due to which the slope of line P_{ab} changes and ultimately the clearance value changes.

Table 11: Coordinates of significant values when vehicle is at yield line

Coordinates of significant points	X-Ordinate (in feet)	Y-Ordinate (in feet)
Coordinates of new centre	$X_n = 2.18$	$Y_n = 8.16$
Coordinates of approach vehicle (Equation 21 and 22)	$X_a = -11.84$	$Y_a = 78.96$
Coordinates of point “e” (Equation 6 and 7)	$X_e = 11.84$	$Y_e = 70.09$
Coordinates of conflict point (Equation 11 and 12)	$X_c = 65.35$	$Y_c = -11.97$
Total Distance travelled from conflict point $(0.278 * V_c * t_c) = 117.42$ ft or 35.79 m		
Coordinates of circulating conflicting vehicle (Equation 19 and 20)	$X_b = 44.13$	$Y_b = -3.75$
Clearance (Equation 29)	14.653 (The value of which depends on X_g and Y_g , which further depend on value of X_f and Y_f which are input values)	

5.1 Validation of equations through AutoCAD

For validating the analytical research work in preceding study, the input readings were plotted on AutoCAD and the results obtained has been shown in fig 33 below.

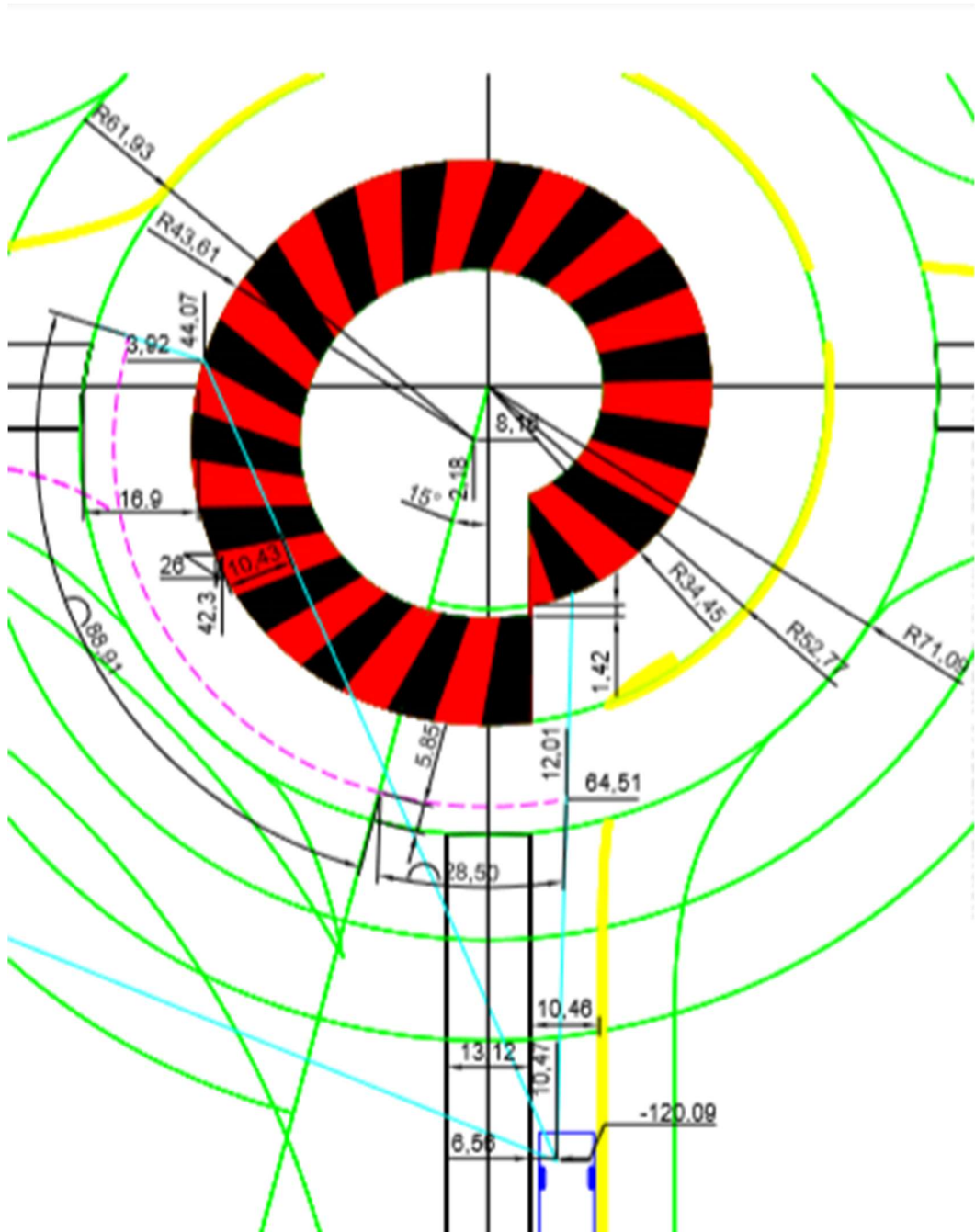


Figure 33: Validation of equations through AutoCAD

The values obtained during graphical analysis were juxtaposed with results of variables calculated by means of mathematical equations in a tabular form as shown in Table 12 below:-

Table 12: Comparison of results of analytical & Graphical Approach

S.No	Variables and coordinates of Turbo Roundabout	Symbol assigned to Variable	Results as per analytical equation	Results as per graphical analysis on AutoCAD	Equations used
1	Origin X-Coordinate	X_0	0	0	Input Data
2	Origin Y-Coordinate	Y_0	0	0	Input Data
3	Initial Radius	R_1	34.45 feet	34.45 feet	Input Data
4	Second Radius	R_2	43.61 feet	43.61 feet	$R_2 - R_1 = ((W_c + f)/2)$
5	Third Radius	R_3	52.77 feet	52.77 feet	$R_3 - R_2 = ((W_c + f)/2)$
6	Fourth Radius	R_4	61.93 feet	61.93 feet	$R_4 - R_3 = ((W_c + f)/2)$
7	Fifth Radius	R_5	71.09 feet	71.09 feet	$R_5 - R_4 = ((W_c + f)/2)$
8	Entering approach width	W_1	10.46 feet	10.46 feet	Input Data
9	Shift	f	1.42 feet	1.42 feet	Input Data
10	Circulatory roadway width	W_c	16.90 feet	16.9 feet	Input Data
11	Median Width	W_M	13.12 feet	13.12 feet	Input Data
12	Distance between the driver's eye and edge of median	A_1	6.56 feet	6.56 feet	Input Data
13	Distance between the driver's eye and outer edge of circulatory roadway width	A_2	5.85 feet	5.85 feet	Input Data
14	Angle between Y-axis and primary translation axis	θ_T	0.26 radians Or 15°	15°	Input Data
15	X-Coordinate of point "f"	X_f	42 feet	-42 feet	Input Data
16	Y-Coordinate point "f"	Y_f	26 feet	-26 feet	Input Data
17	X-Coordinate new center	X_n	2.18 feet	-2.18 feet	$x_n = \frac{W_c}{2} \sin \theta_T$
18	Y-Coordinate new center	Y_n	8.16 feet	-8.16 feet	$y_n = \frac{W_c}{2} \cos \theta_T$

19	X-Coordinate of approach vehicle	X_a	-10.47 feet	10.47 feet	$x_a = \frac{W_m}{2} + W_1 - A_1$
20	Y-Coordinate of approach vehicle	Y_a	120.09 feet	-120.09 feet	$y_a = R_5 + L_{min}$
21	X-Coordinate of conflict point	X_c	-11.97 feet	12.01 feet	$x_c = \{(R_5 - A_2)^2 - y_c^2\}^{0.5}$
22	Y-Coordinate of conflict point	Y_c	65.35 feet	- 64.51 feet	$y_c = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$
23	X-Coordinate of circulating conflicting vehicle	X_b	44.13 feet	-44.07 feet	$x_b = (R_2)\cos\theta_b + \frac{W_c}{2}\sin\theta_T$
24	Y-Coordinate of circulating conflicting vehicle	Y_b	-3.75 feet	3.92 feet	$y_b = -(R_2)\sin\theta_b + \frac{W_c}{2}\cos\theta_T$
25	Distance covered by vehicle between point 'c' and 'z'.	d_3	11.43 feet	28.50 feet	$d_3 = \theta_3 \times (R_5 - A_2)$
26	Distance covered along arc subtended by the angle θ_T	d_2	17.07 feet		$d_2 = \theta_T \times (R_5 - A_2)$
27	Rest of the distance which can be found out by subtracting '(d ₁ +d ₂)' from total distance 'd'.	d_1	88.91 feet	88.91 feet	$d = 0.278V_c t_c$ $d_1 = d - (d_2 + d_3)$
28	Lateral Clearance at point "f"	C_f	10.029	10.43	$C_f = \frac{(R_2) - \sqrt{(x_g - x_n)^2 + (y_g - y_n)^2}}{2}$

It was observed from the above comparison table 12 that the values obtained in table 10 which were derived using analytical equations in chapter 4 approximately matches with the coordinates values of obtained by graphical approach in fig 33. Thus, graphical results obtained validate results deduced by analytical method. Moreover, on closely observing table 12 we can see that the input values are exactly same in analytical and graphical method which is understandable, but the exact same value of all other radius, coordinates of approach vehicle, coordinates of new centre and distances d₁, d₂, d₃ are due to the simple mathematical equations used which are described in the above table. The simple addition, subtraction and trigonometry explains why it gives us the same value. However, a little variation is observed in variable coordinates of conflict point and

coordinates of circulating conflicting vehicle and clearance all of which uses a little complex mathematics. In case of coordinates of circulating conflict vehicles, we use complex quadratic equations for which the values of “a”, “b” and “c” further depend on number of other parameters, in case of clearance and coordinates of circulating conflict vehicles the equations uses variables which further depend on number of other parameters; all of these reasons explains the variation observed in these 3 cases. Although there is difference in the coordinate sign value of the fig 33 and table 10, but the sign of coordinate values of table 10 are justified by assumption 4 in article 4.2. Hence our analytical equations are true and validated.

6.0 Conclusion

The conflict points and thus crash frequency increases when modern roundabouts functions on multi-lanes in comparison to their working on single lanes. Comparative studies suggested that the Turbo roundabouts are the most viable solution for increased safety and efficiency on these multi-lane intersections. Studies also show that barring a few situations capacity at turbo roundabouts significantly increased by nearly one third. The different shapes of turbo roundabouts can be decided catering to different quantum, pattern and movement of traffic. Various geometric features have to be provided with turbo roundabouts, but guidelines published in different countries are not in consensus with their dimensions and provision. These geometric elements are greatly influenced by or influences sight distances. In the study Intersection sight distance was analytically calculated and established using sight lines and sight triangles which help the drivers of conflicting vehicles to see the approaching vehicles. Graphical method though in great use was cumbersome so ready to use equations were derived, verified and established using practical application. It was concluded during research that:-

- Double lane roundabout has more crashes when compared to the single lane roundabout. The difference is in property damage clashes rather than injury collisions.
- Crashes at multi-lane roundabouts are reduced drastically when turbo roundabouts are constructed.
- Capacity at turbo roundabouts are believed to be more but more research and study must be done to validate these facts.
- In terms of capacity turbo roundabouts are effective in case of heavy vehicle flow as long as capacity of the intersection is analysed using the right passenger equivalent factor i.e. E_T which is different for different percentage of heavy vehicles and different entry instead of a single value as suggested by HCM.
- Long combination vehicles can manoeuvre safely if the geometric feature of raised mountable divider and truck apron is provided at turbo roundabout intersection. These features help the vehicles to manoeuvre by accommodating their extra turning space. This concept is especially useful in urban areas where there is high percentage of articulated

buses i.e. A-BUS are there. These buses also use truck apron and raised mountable divider to turn in case of scarcity of space.

- Turbo blocks are established as a foundation of the turbo roundabout, where circular arcs are drawn whose radius changes every time after primary translation axis.
- Intersection sight distance is established to increase the safety perspective, but if the designer provides more than intersection sight distance it may increase crash rate. Landscaping techniques can be used to restrict sight lines.
- Equations which were developed analytically are in general form and are ready-to-use tools for calculation of sight distances and clearances. They were also validated through a practical application.

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