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EFFECT OF VEHICLE COMPOSITION AND DELAY ON ROUNDABOUT CAPACITY UNDER MIXED TRAFFIC CONDITIONS

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Abstract: *Roundabouts are replacing conventional unsignalized intersections in many parts of the world (Polus and Shmueli, 1997). Capacity estimation is necessary for designing a new roundabout, to analyze and improve the existing roundabout facilities. There are several methods to estimate the capacity of the roundabout, but most of them are for homogeneous lane based traffic conditions and not applicable for mixed traffic conditions. This study tries to find out the applicability of the existing methods to mixed traffic conditions, identify the effect of vehicle composition, travel time and delay on capacity. In this study, data was collected from two roundabouts located in Mysore, Karnataka and Rajahmundry, Andhra Pradesh in India. Capacities for both the roundabouts are calculated using the existing methods and compared. VISSIM simulation model has been developed and analyzed for different vehicle compositions scenarios. It was observed that vehicle composition of the traffic influences the roundabout capacity. Since the entry capacity of a roundabout varies significantly with the vehicle composition of the traffic at the roundabout, it is necessary to incorporate this factor into the existing capacity estimation models.*

Key words: *critical gap, vehicle-type, delay, capacity, simulation, circulating flow.*

1. Introduction

A roundabout is a type of unsignalized traffic intersection characterized by yield on entry and circulation around a central island. Traffic in the circle has priority and entering vehicles must yield. Roundabout capacity estimation methods can be classified into three broad categories – weaving theory models, empirical models and analytical models. With the introduction of the offside priority rule, models based on weaving theory have become invalid (Ashworth et al., 1973). Analytical models are based on gap acceptance behavior of vehicle drivers entering a roundabout. In these models, approach capacity is calculated as a mathematical function of critical headway and follow-up headway. The critical gap is the smallest gap that a driver is willing to accept to merge with the circulating traffic and mainly determines the gap acceptance behavior of the driver. Critical gap depends among other factors, vehicle type and the target lane (Kusuma et al., 2011). It is then safe to say that capacity will depend on vehicle composition of the mixed traffic. To estimate critical gap, Raff's method is very reliable and is simple (Antonio et al., 2013). Follow-up headway is the minimum headway between two entering vehicles, which can be calculated by the average difference between passage times of two entering vehicles accepting the same mainstream headway under a queued condition. Methods that are purely based on gap acceptance behavior are not sensitive to roundabout geometric parameters. Empirical methods are based on roundabout geometrics and regression. Methods such as Kimber's method state that dependence of entry capacity on circulating flow depends on the roundabout geometry. Entry width and flare, inscribed circle diameter, angle of entry and radius of the entry are some of the geometric parameters affecting capacity. Similarly, raised lane dividers for circulating traffic, typically used as part of turbo-roundabouts affects the speeds of vehicles and are effective in reducing crashes (Chodur and Bak, 2016). Raised lane dividers are more effective than lane separators in the form of continuous line for turbo-roundabouts (Macioszek, 2015). Chris et al. (2013) have found that gap-acceptance parameters should be adjusted for the percentage of trucks in the entry and circulating flows for an improved accuracy of roundabout capacity prediction. Besides circulating flows, exiting flows and lateral position of the vehicles and geometric parameters have shown significant influence on roundabout entry capacity (Al-Madani, 2012). This study tries to identify the influence of vehicle composition on entry capacity. VISSIM can estimate capacity with more precision using geometric and driver characteristics unlike the other capacity estimation models (Ramu et al., 2015). VISSIM provides simulation results that better matches field conditions and traffic engineering principles. It also has better 3D capabilities, matches the expectation or perception of reviewing agencies (Nedal et al., 2009). Thamizh et al. (2005) described a methodology that was adopted to simulate the flow of heterogeneous traffic with vehicles of static and dynamic characteristics that range widely. They have discussed the common issues related to simulation of heterogeneous traffic such as vehicle generation, vehicle placement and logics for vehicular movement. A study by Vincenzo et al. (2008) was useful in understanding the sensitivity of the VISSIM simulation models to different input parameters such as inscribed circle radius, splitter island width and circulating roadway width.

From the literature review, it is observed that, in mixed traffic conditions, both non-motorised vehicles and motorized vehicles of all types share the same carriageway. Vehicle composition is varied and usually has a good proportion of two-wheelers, unlike a uniform traffic of passenger cars as in homogeneous traffic conditions. Also, in mixed traffic conditions, drivers do not usually follow lane discipline and can occupy any lateral position on the road. However, most of the models estimate roundabout capacity based on lane-based motorised traffic. Therefore, results based on these models will not be able to give reliable results for mixed traffic conditions. They are to be calibrated for such conditions and additional parameters that account for traffic heterogeneity and lateral behavior are to be introduced. The present study tries to identify the influence of vehicle composition on entry capacity. For comparison, seven different methods are used which includes: Highway Capacity Manual (HCM) 2010, Tanner, Troutbeck, Hagring, Siegloch and Tanner - Wu methods, which are analytical models and the German Empirical method. Hence, it is necessary to identify how the above discussed parameters influence roundabout capacity in mixed traffic conditions.

2. Study area and data analysis

Two roundabouts located in Mysore city, Karnataka (Roundabout-1) and Rajahmundry, Andhra Pradesh (Roundabout-2) in India were selected for the study. Both the roundabouts consist of two entry lanes on all legs, two circulating lanes and have quite low heavy vehicle traffic through it. The diameter of the central island is 9 meters and 8.6 meters respectively. For these roundabouts, following parameters were extracted from the captured video: vehicle arrival rate, gap between the vehicles, traffic volume, total delay, circulating vehicles headway, vehicle type. The line diagram for both the roundabouts is shown in Fig 1 and 2. The video-graphic data were taken from elevated positions for a period of two hours during weekdays on each location. The data from the video was extracted using Media Player Classic, at an accuracy of 1 in 1000 seconds (0.001 s).Critical gap is estimated using Raff's method. The peak hour distribution of the traffic which includes two-wheelers (2w), three-wheelers (3w), four-wheelers (Car), light commercial vehicles (LCV), buses, bicycles, heavy vehicles (HV).

Table 1 and 2 shows the composition of traffic for both the roundabouts. It can be observed that the proportions of two and three wheelers are very high compared to other modes due to the location of roundabouts closer to residential area.

Critical gap is estimated using Raff's method. The extracted data of accepted and rejected gaps is sorted by gap length. For every gap length, the cumulative numbers of gaps accepted are tabulated. Similarly, for every gap length, the cumulative numbers of gaps rejected are found out. A graph is plotted using these two data sets. The intersection point of these two curves gives the critical gap (t_c) value. Fig3 shows the critical gap estimated for NB approach of Roundabout-1.

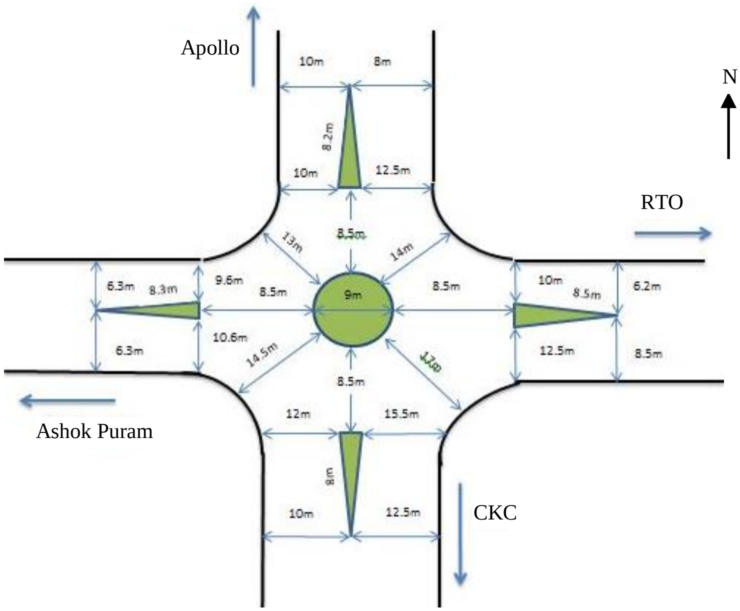

Fig. 1. Geometry of Roundabout-1

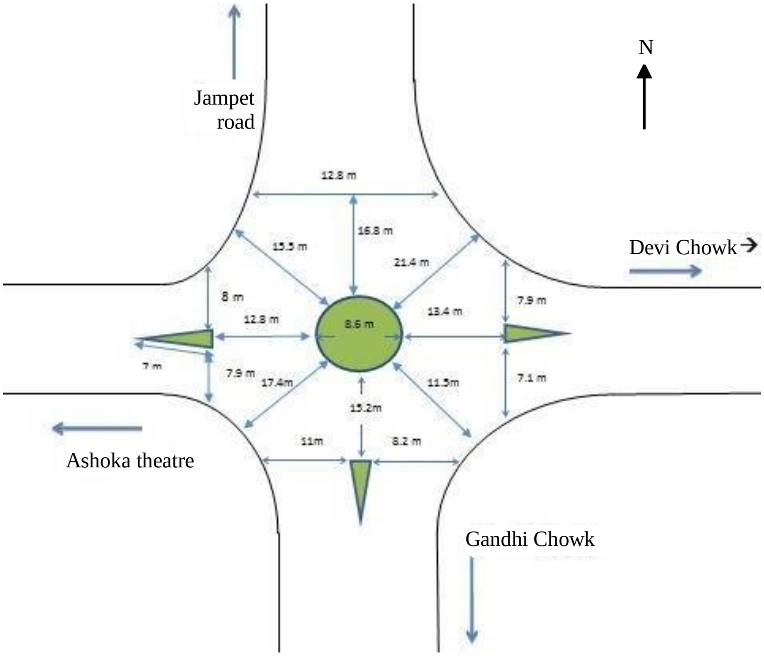

Fig. 2. Geometry of Roundabout-2

Table 1. Composition of traffic at Roundabout-1

Leg of Intersection	Car	2W	Bus	LCV	Bicycle	HV	3W	Total	Total (PCU)
NB	178	894	29	31	42	16	137	1327	963
EB	107	780	2	17	26	2	117	1051	682
WB	39	521	2	8	34	4	52	660	400
SB	123	930	38	42	34	8	110	1285	901

Table 2. Composition of traffic at Roundabout-2

Leg of Intersection	Car	2W	Bus	LCV	Bicycle	HV	3W	Total	Total (PCU)
NB	74	840	0	13	39	0	204	1170	774
SB	44	770	2	14	21	0	79	930	558
EB	36	417	0	0	42	0	210	705	513
WB	74	502	0	18	42	0	270	906	693

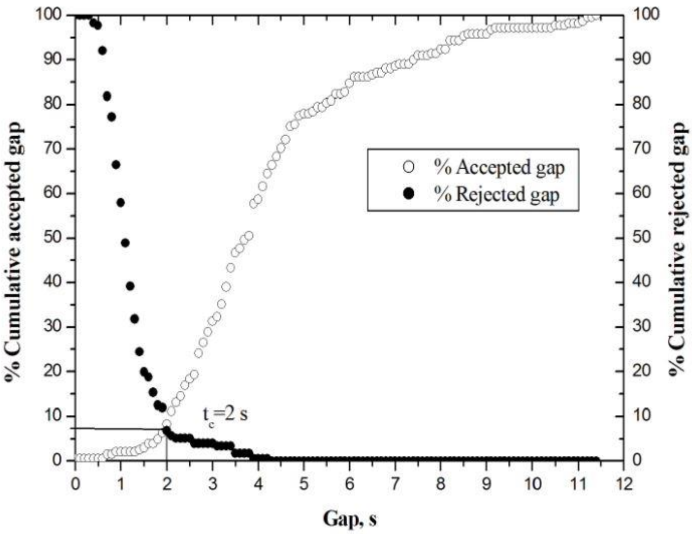

Fig. 3. Critical gap for NB of Roundabout-1

Table 3. Critical gap and Follow-up gap for both the Roundabouts (in seconds)

Leg of the Roundabout	Roundabout-1		Roundabout-2	
	Critical gap	Follow-up gap	Critical gap	Follow-up gap
NB	2.00	1.73	2.65	3.46
SB	2.10	3.12	2.80	2.91
EB	3.25	7.44	3.35	3.85
WB	2.40	8.86	3.10	4.62

The critical gaps and follow-up times for both the roundabouts are tabulated in table 3. The least value amongst the gaps between circulating vehicles gives Δ, the minimum gap between circulating vehicles. For Roundabout-1 and 2, the values were found to be 0.08 seconds and 0.24 seconds. Such low values have been observed because in mixed traffic conditions the vehicle does not travel in proper lane and tries to cross the intersection in a minimum possible gap. These are the input parameter for Tanner, Troutbeck and Hagring models.

Lower critical gap values were obtained at approaches carrying higher traffic. At both the roundabouts, lower critical gaps were observed for major roads and higher critical gaps for the minor approaches. Also, the follow-up times for the minor approaches are higher compared to that of major approaches. The difference is even more evident in the case of Roundabout-1.

Using the above data, capacity values are estimated for both the roundabouts using seven methods listed earlier. Leg-wise traffic volumes, percentage of heavy vehicles, peak hour factors and lane configuration are used to estimate capacity. Also, the above determined parameters i.e, critical gap, follow-up time and minimum circulating gap are necessary in estimating capacity by the analytical methods. The capacity values thus estimated for both the roundabouts are shown in the Table 4.

Table 4. Entry capacity estimated by different models(PCU/hr)

Capacity Estimation Method	Roundabout-1				Roundabout-2			
	NB	SB	EB	WB	NB	SB	EB	WB
HCM 2010	1074	1463	707	534	907	894	672	698
Tanner	918	722	291	343	895	886	654	672
Troutbeck	1186	757	319	322	1024	939	702	770
Hagring	1317	2309	790	780	1493	1242	1021	1195
Siegloch	873	1174	211	244	648	672	435	454
Tanner -Wu	2148	2925	1414	1068	811	993	926	851
German Empirical	544	730	517	349	471	655	636	580

3. Simulation

The roundabout or traffic network is drawn to scale in VISSIM simulation tool making use of the dimensions collected from field. The traffic data extracted from the videos is given as vehicle inputs to simulate field conditions in VISSIM. Routing and priority rules have been set accordingly and traffic entering the roundabout has priority over the circulating traffic. Car following model parameters have been calibrated with values suggested by a similar study conducted at IIT Delhi (Ramu et al., 2015). Six runs of simulation are performed and the average of these six sets of output values are used in further calculations. The simulation and corresponding analysis have been done for Roundabout-1.

Since it was not practical to collect traffic data at capacity conditions, capacity of the roundabout has been estimated using VISSIM simulation. The entry traffic volumes have been increased in 10% steps and simulated till a maximum and constant circulating traffic has been obtained. This represents the capacity conditions**.** At entry volumes 60% higher than field volumes, capacity conditions were attained. Entry capacities of the roundabouts are then estimated from the circulating flow using HCM 2010 method. The capacities thus estimated are shown in Table 5. Comparison of traffic volumes obtained from the field and VISSIM are tabulated in Table 6.

Entry capacity of a roundabout varies significantly with the vehicle composition of the traffic at the roundabout. The entry capacities for four approaches of Roundabout-1 are calculated using the seven methods and compared with VISSIM simulation result as shown in Fig. 4. HCM 2010 method seems to be giving capacity values that are similar to those estimated by simulation in VISSIM.

Table 5. Entry capacities estimated from simulation for Roundabout-1

Leg of Intersection	Entry Capacity (PCU/hr)
NB	1245
EB	782
WB	514
SB	1075

Table 6. Comparison of traffic volumes obtained from the field and from VISSIM simulation (number of vehicles)

Leg of Intersection	VISSIM				Field data			
	Left	Through	Right	Total	Left	Through	Right	Total
NB	224	905	52	1181	295	967	64	1326
EB	331	218	172	721	487	297	266	1050
WB	100	473	64	637	72	521	66	658
SB	22	532	357	911	47	739	557	1284

These values also seem to be correct when compared to field volumes. Hagring and Tanner-Wu methods are overestimating the capacity, while Tanner, Siegloch and German empirical method seems to be predicting lower values. While the German empirical method's lower estimations can attributed to its few input parameters, there seems to be no such reasons for the others.

4. Effect of vehicle type on entry capacity

As discussed earlier, the effect of vehicle composition on the capacity of a roundabout has not been studied so far. Attempt has been done making use of the VISSIM simulation tool and six different vehicle compositions have been created for this purpose. VISSIM simulation has been run for each of these compositions with the field traffic volume being given as vehicle inputs. The vehicle compositions adopted by VISSIM and the Capacities of roundabout-1 for different vehicle compositions are shown in Table 7.

Entry capacities are calculated from the VISSIM volume outputs using the HCM 2010 method. The entry capacities thus calculated are shown in Table 8. It can be concluded from the results that entry capacity changes with vehicle composition. Though the capacity values of the SB approach did not show any variation, the other three approaches have shown substantial variations. It can also be seen that as the percentage of two-wheelers in the traffic decreased and the percentage of heavy vehicles increased, the capacity values have increased.

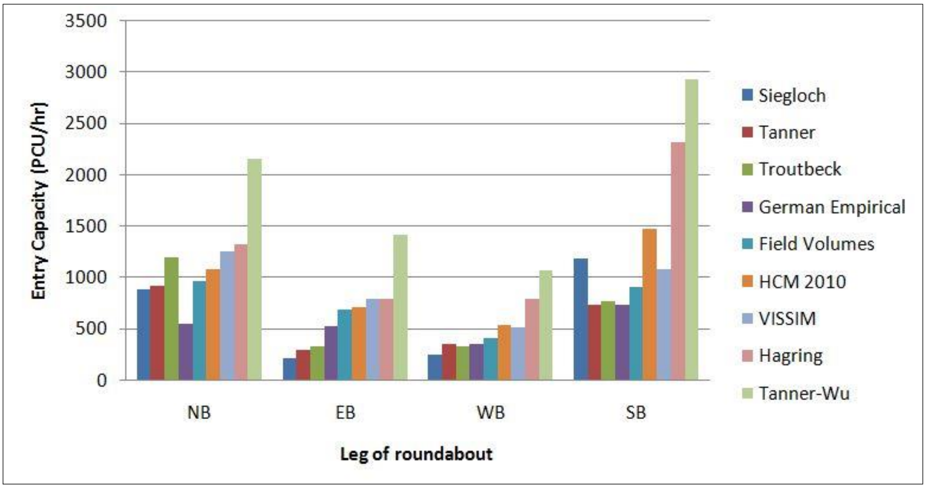

Fig. 4. Comparison of capacities of Roundabout-1 estimated using different methods.

Table 7. Vehicle compositions and Capacities adopted for VISSIM

Composition	Vehicle Composition by VISSIM (%)							Capacity of Roundabout-1(PCU/hr)			
	2W	HV	Car	3W	Bus	LCV	Bicycle	NB	EB	WB	SB
C1	70	0	10	10	3	3	4	924	369	618	1080
C2	60	10	10	10	3	3	4	1243	497	807	1076
C3	50	20	10	10	3	3	4	1564	627	982	1077
C4	40	30	10	10	3	3	4	1991	750	1093	1083
C5	50	30	5	5	3	3	4	1996	724	975	1090
C6	0	0	100	0	0	0	0	1311	513	771	1085

5. Relationship between Entry Capacity and Circulating Flow

Different methods suggest a different relationship between the entry capacity and circulating flow at a roundabout. Some methods, such as HCM and Seigloch's methods suggest a negative exponential relation between these two variables while others such as, Kimber and German empirical methods show a linear relationship. The circulating volumes versus their corresponding entry capacities graphs at each leg of the roundabout are shown below in Table 8. A negative exponential relationship between the circulating flow and entry capacity is observed to be giving the best fit.

Table 8. Entry capacity versus Circulating flow

Leg of Intersection	Equation	R^2
NB	$y = 1153.74e^{-0.00015x}$	0.998
SB	$y = 2071.91e^{-0.00038x}$	0.998
EB	$y = 522.34e^{0.00036x}$	0.621
WB	$y = 493.33e^{0.00010x}$	0.646

6. Travel time at the Roundabout

The total time spent by through and right turning traffic at the roundabout is estimated. The difference between a vehicle exit and entry times gives the total travel time of the vehicle in the roundabout. The travel time for different vehicle classes for Roundabout-1 are shown in Table 9. The average travel time of all vehicle types calculated direction wise are listed in Table 10.These travel time values seem to be following the general trend that bicycles and heavy vehicles have higher travel times compared to two-wheelers and cars. Also, the traffic from minor roads, i.e, from EB and WB are experiencing higher travel times compared to traffic from major roads. There are no buses taking a right turn at the roundabout.

Table 9. Average travel time of vehicles types at Roundabout-1 (seconds)

Vehicle type	Through	Right
2W	6.06	9.64
Car	6.11	10.97
3W	6.49	9.54
LCV	6.49	11.01
HV	6.87	11.16
Bus	7.27	-
Bicycle	9.78	12.76

Table 10. Direction wise average travel time of all vehicle types at Roundabout-1 (seconds)

Leg of intersection	Through	Right
NB	5.67	9.98
EB	7.42	9.24
WB	7.71	14.09
SB	5.55	9.58

To analyze the performance of the roundabouts their level of service are estimated. For roundabouts, as per HCM 2010, control delay is the only measure of performance. The HCM 2010 suggests the following model as shown in Equation (1) to estimate average control delay of a roundabout approach.

$$d = \frac{3600}{C} + 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{\left(\frac{3600}{C}\right)x}{450T}}\right] + 5 \cdot \min[x,1] \quad (1)$$

where:
d = average control delay (s/veh),
x = volume-to-capacity ratio of the subject lane,
C = capacity of the subject lane and,
T = time period (h).

The control delay for the intersection as a whole is calculated by computing a weighted average of the delay for each approach, weighted by the volume on each approach. Accordingly the control delays have been calculated and the level of service of Roundabout 1 and 2 have been estimated and shown in Table 11.

Table 11. Control delay and LOS

Leg	Roundabout-1		Roundabout-2	
	Control delay (s)	LOS	Control delay (s)	LOS
SB	28.06	D	23.94	C
NB	9.41	A	13.18	B
EB	32.38	D	22.71	C
WB	27.95	D	20.92	C
Intersection	23.55	C	19.62	C

7. Conclusions

Though the concept of gap acceptance is quite complex, methods developed based on it are simpler, require fewer input parameters and give reasonable results. HCM 2010 method was observed to be giving capacity values that are similar to those estimated by VISSIM simulation. These values found to be correct when compared to field volumes. Hagring and Tanner-Wu methods are overestimating the capacity, while Tanner, Siegloch and German empirical method was observed to be predicting lower values. While the German empirical method's lower estimations can attributed to its few input parameters, there seems to be no such reasons for the other models. Apparently, the field conditions in which the models were calibrated make the difference. Travel times of bicycles and buses are the highest while, travel times of two wheelers is the least. Traffic from minor roads experience higher travel times compared to traffic from major roads. Two-wheelers are able to accept the least lengths of gaps available. The critical gap value is estimated to be the least for two-wheelers. Due to their very low volumes, critical gap values for buses and heavy vehicles could not be estimated. Entry capacity of a roundabout varies significantly with the vehicle composition of the traffic at the roundabout. It is therefore, necessary to incorporate this factor into the existing capacity estimation models for them to be applicable to mixed traffic conditions. Both the roundabouts that were studied are estimated to be working at a level of service C. This shows that they are working quite well with the traffic experiencing normal travel times with lesser delays. Both the roundabouts that were selected for data collection are mini roundabouts. Results and trends may vary with size and geometry of a roundabout.

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