Capacity and Level of Service of Roundabouts Using Indo-HCM

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Abstract A roundabout or traffic rotary is an enlarged road intersection where all converging vehicles are forced to move around a large central island in one direction before they can weave out of traffic flow into their respective direction radiating from the central island. In India and other countries which follow "keep to the left" regulations, vehicles move in clockwise direction around the central island. The objective of providing a rotary intersection is to eliminate the necessity of stopping even for crossing streams of vehicles and to reduce the area of conflict. The crossing of vehicles is avoided by allowing all vehicles to merge into the streams around the rotary and then to diverge out to the desired radiating road. Thus, the crossing conflict is eliminated and converted into "weaving maneuver," i.e., merging from the left and diverging out to the right or merging from the right and a diverging out to the left. In this study, two circular roundabout intersections in Hyderabad city are chosen to analyze their operational performance under prevailing traffic composition, flow movements, and geometric conditions by conducting traffic volume and gap-acceptance studies. Both intersections are analyzed and their capacity and level of services (LOS) are estimated as per recently published Indian Highway Capacity Manual (Indo-HCM).

1 Introduction

At-grade intersections are the critical points of a road network where delay normally occurs due to sharing of space and time between conflicting streams of vehicles. Depending upon the type of control employed, intersections can be termed as uncontrolled intersections, stop-controlled intersections, rotaries, signalized intersections, and grade-separated intersections or interchanges. A rotary is a specialized form of

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at-grade intersection where vehicles from the converging arms are forced to move round a central island in one direction in an orderly and regimented manner and weave out of the roundabout into their desired direction.

Typically, roundabouts are classified according to their size and environment to solve design and evaluation of operational performance issues. There are classified based on the number of lanes and size as mini-roundabouts, single-lane roundabouts, double-lane roundabouts, and multilane roundabouts with more than two approach lanes. Mini-roundabouts are small roundabouts of about 4–12 m diameter and are generally provided when there is enough roadway width is not available. Finally, multilane roundabouts with more than two or more lanes are provided to accommodate more than one vehicle traveling side by side. The speeds at the entry on the circulatory roadway and at the exit are similar or may be slightly higher than those for the single-lane roundabouts. These roundabouts can be further subdivided based on their environment such as rural or urban roundabouts. In case of urban areas, consideration should be given for pedestrians, bicyclists, and large vehicles with low design speed. On the other hand, high design speed and large vehicles are considered in rural or non-urban areas.

In any of the above conventional roundabout, traffic at entry seek a suitable gap in the circulating stream to negotiate at the roundabout. Since these intersections are characterized by complex vehicular movements such as merging and diverging and to ensure safety of these vehicles, it is necessary to study them to arrive at capacity and level of service (LOS) under different operating conditions. Capacity of a roadway facility is defined as the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time under the prevailing roadway, traffic, and control conditions. Under mixed traffic conditions, it is necessary to bring all the vehicles to a common type, usually the passenger car. The capacity is then expressed in passenger car units (PCUs) per hour.

On the other hand, level of service is used to refer congestion level. When a road is carrying a traffic volume equal to its capacity under ideal roadway and traffic conditions, the operating conditions become poor. Speed drops down, and the delay and frequency of stops mount up. Thus, the concept of level of service is defined as a qualitative measure describing the operational conditions within a traffic stream and their perception by motorists. Typically, in case of roundabouts, delay caused by queueing of vehicles at entry and by geometry is used as a standard parameter to measure the operational performance of a roundabout. The objective of the present study is to determine the capacity and level of services of chosen roundabouts under various geometric and traffic flow conditions. Having been introduced about roundabouts capacity and their operational performance, a comprehensive literature review on roundabouts with respect to the stated objective is presented below.

Macioszek and Akçelik [1] compared two roundabout capacities models such as Macioszek model and SIDRA model in their study. Both models were based on gap-acceptance theory with an exponential distribution of circulating road headways, but their headways and capacity distributions are calibrated for two different traffic conditions prevailing in Poland and Australia. Vasantha Kumar et al. [2] studied a five approach multi-leg roundabout by conducting a traffic volume survey using video data collection. They found that the proportion of weaving traffic as 0.81 and then estimated required weaving width and lengths. They also estimated the capacity of the roundabout as 3020 PCU/h using TRL equation. Giuffrè et al. [3] analyzed modeling issues at multilane roundabout specifically, minor drivers' failure to obey stop or yield control. They found that existing operational models do not incorporate interdependencies between entering and circulating vehicles at multilane roundabouts. To account for this, an analytical capacity model is derived from field observations. Giuffrè et al. [4] reviewed measurement of two gap-acceptance parameters such as critical gap and follow-up times for various roundabouts across the world. They found that size of the roundabout such as single-lane/turbo influenced the gap-acceptance parameters. Finally, they have developed a single meta-analytic estimate to represent various roundabouts. Manage et al. [5] reviewed various capacity and delay models of various intersections and modified to suit Japanese traffic conditions. Finally, a roundabout was proposed as an alternative to signalized control, and they found it is promising under low traffic conditions. Mathew et al. [6] studied Indian roundabout capacity under heterogeneous traffic conditions. They found that relationship between entry flow and circulatory flow follows a negative exponential behavior, i.e., the entry capacity reduces exponentially with the increase in circulating flow. Finally, authors estimated stream equivalency factors for critical gap and follow-up times under mixed traffic conditions and a multiplicative adjustment factor for HCM 2010 equation to estimate entry capacity under mixed traffic conditions. Vasconcelos et al. [7] used several methods such as maximum likelihood, and logit to estimate gap-acceptance parameters at roundabout. The comparison of estimates with reference values from several countries indicates the existence of relevant driving style differences, which implies that locally calibrated, country-specific, parameters are required for capacity estimations.

2 Analysis of Roundabout

Generally, the roundabout is analyzed by its geometry, traffic flow, and driving behavior characteristics. The geometry of a typical roundabout can be described by its central island diameter, entry radius, entry width, exit radius, exit width, weaving length and width, and splitter island as shown in Fig. 1.

The traffic flow through the roundabout intersection can be broadly divided into entry flow through multiple approaches and circulating flow moving around the central island. The driving behavior of vehicles can be described by analyzing various headways such as gap, and headways are shown in Fig. 2. Gap is defined as the time span between two consecutive circulating vehicles that create conflict with an entering vehicle. Similarly, a headway can be defined as the time span between

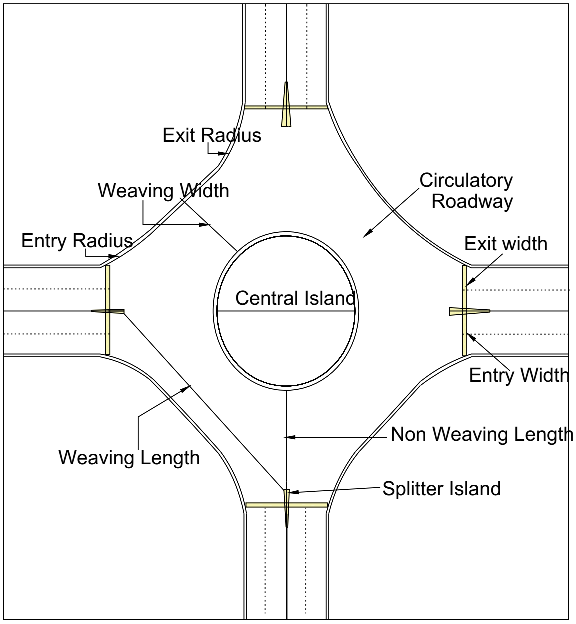

Fig. 1 Geometric elements of a typical roundabout. *Source* [8], pp. 7–4

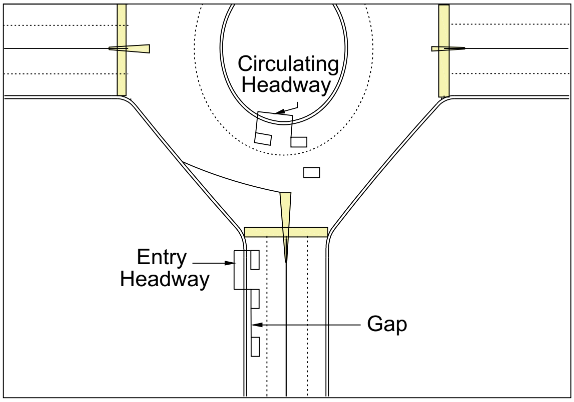

Fig. 2 Measuring gap and headways between vehicles. *Source* [8], pp. 7–6

two following vehicles and is measured from the first vehicle's front bumper to the following vehicle's front bumper.

3 Methodology

The methodology for estimation of capacity and level of service of a given roundabout involves collection of geometric, traffic, and driving behavior parameters. The

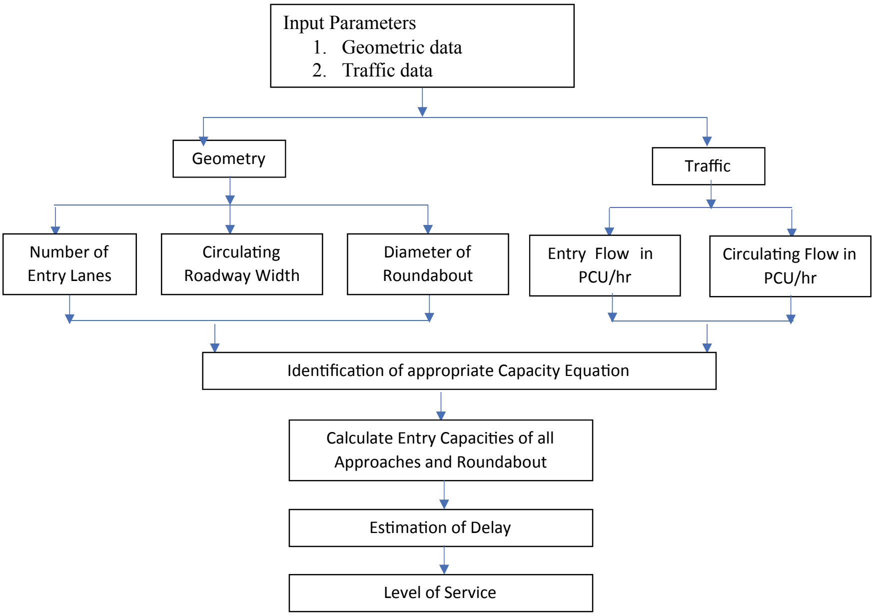

Fig. 3 Methodology flow chart. *Source* [8], pp. 7–8

geometric data includes details such as diameter of roundabout, number of approach lanes, approach width, number of circulating lanes, and circulating roadway width. And, traffic data includes details such as entry flow, circulating flow, and their conversion to passenger car units (PCU). Finally, the driving behavior data includes estimation of critical gap and follow-up time. Based on the above-collected data, suitable capacity equation must be chosen as per Indo-HCM manual [8]. Thereafter, the entry capacity of all approaches and the whole roundabout can be estimated by substituting estimated critical gap, follow-up time, and circulating flow details. The level of service of the roundabout can be estimated by substituting total entry flow from all the approaches and by estimating average delay experienced per vehicle. The above steps are outlined in Fig. 3. The same methodology can be applied for a planning and design of new roundabout by supplying traffic information and the desired level of service (LOS).

4 Data Collection and Extraction

The study area is chosen as KBR park and NTR Marg roundabouts in Hyderabad city. The KBR park roundabout is a three-way intersection with 40 m diameter central island and 9 m each for entry and exit width for every approach. Similarly, the NTR Marg roundabout is a four-way intersection with 60 m diameter central island and 10 m each for entry and exit width for every approach. The layouts of the study intersections are shown in Figs. 4 and 5. Apart from collecting geometric data, classified traffic volume surveys are carried out to get the various turning volumes such as entry flows and exit flows for all the approaches. Simultaneously, a separate team of members collected data for circulating flow at all the entries. Since the traffic is characterized by mix of multiple vehicle types, all these vehicles are converted to passenger cars by multiplying with appropriate PCU values as given in Indo-HCM [8]. The PCU values used in the study are given in Table 1. Finally, a gap-acceptance study is carried out by placing video cameras at vantage locations so that it covers entire weaving section, entry, circulating, and exit flows at each approach. Further, cameras are also focussed in such a way that they cover the part of non-weaving section so that available gap in the circulating traffic is visible before being accepted or rejected by the entry vehicle. Similarly, expected queue length at entry is also covered in the recording.

Data extraction was carried out with respect to gap-acceptance parameters such as accepted gap, rejected gaps, and follow-up time for different classes of vehicles and corresponding classified entry and exit flows.

To estimate capacity and level of service of the intersection, various parameters such as critical gap, follow-up time, and average delay of the vehicle must be estimated. Critical gap represents the minimum time gap in the circulating flow of vehicles when an entering vehicle from approach can safely enter a roundabout, whereas follow-up time is the headway corresponding to saturation flow rate for the approach if there were no conflicting vehicles from circulating flow. In addition, the delay can be defined as the additional time experienced by the vehicle from the

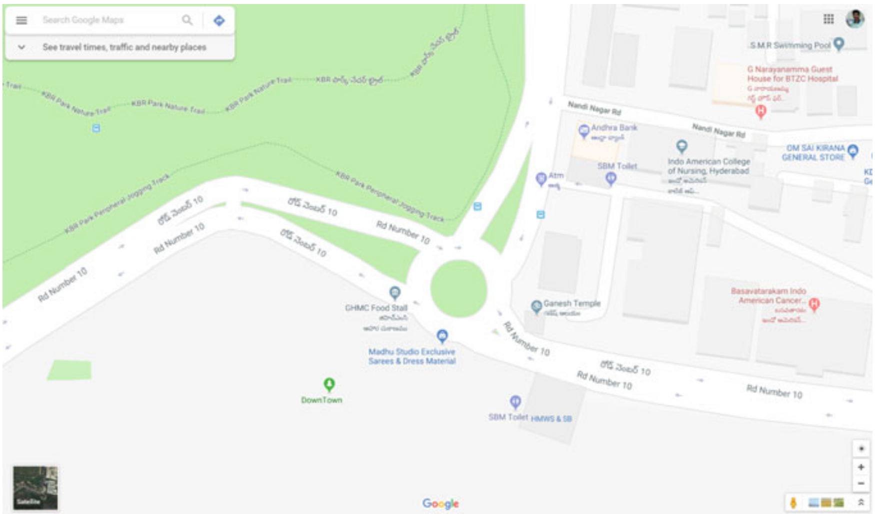

Fig. 4 Layout of the KBR park roundabout. *Source* Google Map

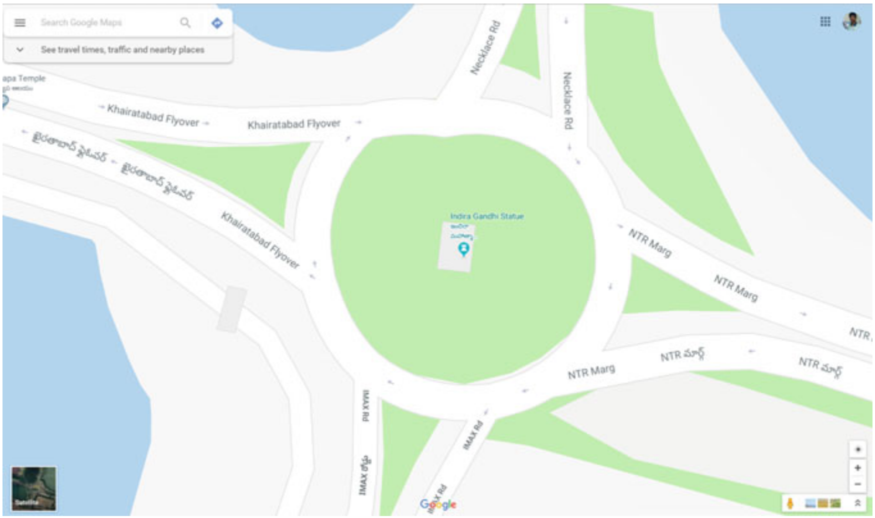

Fig. 5 Layout of the NTR Marg roundabout. *Source* Google Map

Table 1 Passenger car units

Dia (m)	TW	Auto	Small car	Big car	LCV	Heavy vehicle	Cycle
KBR (40)	0.32	0.83	1.0	1.4	1.53	3.2	0.25
NTR Marg (60)	0.32	0.83	1.0	1.4	1.46	3.05	0.28

Source [8], pp. 7–10

entry point to reach the exit point of the intersection. These parameters are further discussed in the subsequent sections.

4.1 Calculation of Critical Gap (T_c)

Critical gap is a parameter that depends on local conditions such as geometric layout, driver behavior, vehicle characteristics, and traffic conditions. However, critical gap cannot be measured directly in the field or from recorded events. The critical gaps are estimated based on the technique related to the accepted and maximum rejected gaps using root mean square method. Root mean square (RMS) is an analytical model where the minimization of square root of the mean squared deviation of predicted value from a given baseline or fit gives the absolute measure fit. Critical gap estimation requires information about the accepted gap and the maximum rejected gap for each driver. RMS model minimizes the square root of the mean squared deviation of rejected gap value R_i and accepted gap value A_i from expected critical gap value T_c to give the average critical gap value. The function depicting the estimation of critical gap is given in Eq. (1) (Indo-HCM) [8].

$$\mathrm{RMS} = \mathrm{Min}\left[\sum_{i=1}^{n} \sqrt{\frac{(A_i - T_c)^2 + (T_c - R_i)^2}{2}}\right] \tag{1}$$

where

A_i Accepted gap of the ith entering vehicle (*seconds*)
R_i Highest rejected gap of the ith entering vehicle (*seconds*) and
T_c Critical gap value (*seconds*)

Using solver option in Microsoft EXCEL, function minimization can be carried out which is basically an iterative process and the first value for iteration must be logical. It would be good to use average of all the highest rejected gaps and all accepted gaps as a first value or starting point so that it can converge fast and reduce the number of iterations. Critical gap estimation is enumerated within the Excel worksheet as presented in Table 2. The values in column 2 and column 3 are the maximum rejected gaps (R_i) and accepted gaps (A_i), respectively. The initial value of $T_c = 3.23$ s is given as input to start the iteration in solver, which is an average of all accepted and rejected gaps. This is used to calculate the value of RMS function as given in the last column. The sum of the function is given in the last row. The iteration process is started using the solver function in MS EXCEL to get the minimum value of sum of root mean squared values. The iterative process utilized helped in converging the function value from 17.31 to 17.20, the convergence was achieved at $T_c = 3.01$ s, which is the estimated critical gap.

4.2 Calculation of Follow-up Time (T_f)

Follow-up time is measured at the stop line of the entry between the vehicles using the same gap in circulating flow. The vehicles on entry leg should be in a queuing position following each other while accepting the same gap in circulating flow. Follow-up time is the time between two entering vehicles, front to front, which can be calculated by the average difference between the passage times of two entering vehicles accepting the same mainstream gap under a queued condition. It is to be noted that follow-up time is considered as 0.75 times the critical gap as given in Indo-HCM [8].

5 Estimation of Capacity and Level of Service

The capacity of a roundabout depends on entry angle, lane width, and the number of entry and circulating lanes. Like other types of intersections, operational performance

Table 2 Gap analysis and critical gap estimation

Rejected gap	Max. rejected gap (S)	Accepted gap (S)	RMS error
1, 2.32, 1.47, 2.95, 3.17, 2.37, 2.54, 2.89	3.17	3.24	0.20
0.75, 0.57, 1.24, 1.04, 0.68, 1.83, 1.89, 0.48	1.89	3.89	1.01
1.72, 1.62, 1.38, 0.92	1.72	3.56	0.99
0.38, 1.13, 0.16	1.13	2	6.44
1.02, 0.98, 1.35, 1.31	1.35	1.71	1.49
1.77, 0.89, 2.03, 1.63, 2.84, 3.37, 1.80, 1.76, 1.82	3.37	3.96	0.72
1.71, 3.83, 1.80	3.83	4.13	0.98
0.91, 0.97, 1.25	1.25	1.87	1.48
1.16, 1.28, 0.71, 0.97, 0.98	1.28	4.86	1.79
2.43, 1.31	2.43	2.9	0.42
1.58, 1.14, 1.48, 1.66, 1.76, 2.06, 2.90, 1.76, 1.57, 1.59, 2.31, 2.42, 1.60	2.9	3.07	0.09
1.58, 1.24, 1.54, 0.95, 1.07, 1.62	1.62	4.78	1.59
Average	2.16	4.16	Sum 17.20
Critical gap T_c		3.01	
Follow-up time T_f		2.3	

depends heavily on the volume of vehicles entering from all approaches. Many studies on roundabout capacity have been carried out in multiple countries. Most widely used Transportation Research Laboratory (TRL) models were developed based on the geometric parameters of the roundabout and driving behavior of the road users. Australian Road Research Board (ARRB) models differ from the TRL model significantly, following a lane-based gap-acceptance theory including geometric parameters. Sidra Intersection software includes roundabout capacity models developed in Australia and the USA. The highway capacity model (HCM 2010) developed by Transportation Research Board (TRB) combines a gap-acceptance model along with exponential regression and can be calibrated by estimating the critical headway and follow-up headway. According to Indo-HCM [8], the capacity of a roundabout is a function of entry flow, circulating flow, critical gap, and follow-up time as given below:

$$C = A \times \text{Exp}(-B \times Q_c) \quad (2)$$

$$A = 3600/T_f \quad (3)$$

$$B = (T_c - 0.5 \times T_f)/3600 \quad (4)$$

where

T_f Follow-up time in *seconds*
T_c Critical gap in *seconds*
Q_c Circulating flow in PCU/h

Therefore, capacities of study intersections KBR Park and NTR Marg are estimated as 3024 PCU/h and 7744 PCU/h using above model. Typically, a roundabout operates with less delay than signalized intersections. Roundabouts do not stop all entering vehicles, reducing both individual and queuing delays. However, they can increase delays in locations where high-volume road intersects with low-volume road. The level of service (LOS) of the above study intersections is determined by estimating the average delay experienced by each vehicle using Indo-HCM [8] model as follows:

$$\text{The average vehicle delay } y = 0.8 \times e^{0.001 \times x} \quad (5)$$

where

y Vehicular delay in *seconds*
x Total approach traffic flow in Veh/h

Based on the estimated delay, level of service is classified as per Indo-HCM [8] guidelines given in Table 3.

Table 3 Level of service

LOS	Average delay "*d*" per vehicle (s)
A	≤ 5
B	$6 \leq d \leq 15$
C	$16 \leq d \leq 20$
D	$21 \leq d \leq 35$
E	$36 \leq d \leq 65$
F	>65

Source [8], pp. 7–13

Table 4 Summary of KBR park roundabout level of service

	Ent 1	Ent 2	Ent 3	QC 1	QC 2	QC 3	Delay (s/veh)	LOS
Morning								
7:00–8:00	820	685	429	282	633	584	6	B
8:00–9:00	1342	832	614	464	1063	728	13	B
9:00–10:00	1509	804	1165	968	1287	746	26	D
10:00–11:00	1210	853	1149	794	1082	811	20	C
Evening								
4:00–5:00	1428	904	1111	890	1297	871	25	D
5:00–6:00	1298	1041	942	738	1265	951	21	D
6:00–7:00	1387	759	1137	862	967	695	21	D
7:00–8:00	1230	1017	1147	778	523	953	24	D
Peak hour								
8:45–9:45	1387	759	1137	862	967	695	21	D
4:30–5:30	1536	995	999	799	1361	924	27	D

The summary of the results such as entry flow, circulating flows, delay, and level of service during morning and evening periods at KBR Park and NTR Marg roundabouts are presented in Tables 4 and 5.

6 Conclusion

Roundabouts improve safety by converting crossing conflicts into weaving operations. The geometry of roundabouts such as diameter, width of circulatory flow, and width of entry and exit flows depends on the total traffic volume and share of turning movements passing through the intersection. In the present study, the capacities of KBR Park and NTR Marg roundabouts are estimated as 3024 PCU/h and 7744 PCU/h, respectively. Similarly, level of services of KBR Park and NTR Marg roundabouts during morning and evening peak hours are estimated as D and F, respectively. Furthermore, it may be noticed that the average delay of the vehicle is estimated as 896 s/veh during evening peak at NTR Marg roundabout, such a huge value seems to be unreasonable because there were no stopping and queuing of vehicles during the study period. Therefore, it may be concluded that the exponential model given by Indo-HCM for estimating average delay may not work under such high-volume and geometric conditions.

In general, level of service (LOS) of roundabouts can be improved by diversion of traffic or by increasing widths of entry approaches and circulatory roadways around Central Island. The study identified that the following are the contributing issues to the poor level of service at the above locations: mixed traffic conditions, no lane discipline, lack of enforcement measures, and inefficient and inadequate public

Table 5 Summary of NTR Marg roundabout level of service

	Ent 1	Ent 2	Ent 3	Ent 4	QC 1	QC 2	QC 3	QC 4	Delay (s/veh)	LOS
Morning										
7:00–8:00	224	576	1022	886	778	1462	113	403	12	B
8:00–9:00	336	732	1592	1164	1149	1946	179	522	37	E
9:00–10:00	565	831	1897	1707	1815	2129	232	617	119	F
10:00–11:00	699	573	2304	1028	2533	1801	289	1082	80	F
Evening										
4:00–5:00	356	802	2781	1348	1903	1715	349	674	158	F
5:00–6:00	574	934	4794	1903	3647	2128	451	846	753	F
6:00–7:00	468	1128	1277	2161	3874	2490	635	1336	123	F
7:00–8:00	509	1231	4296	2371	3228	2711	560	1227	896	F
Peak hour										
9:30–10:30	720	744	2138	1412	2307	2217	271	787	120	F
6:00–7:00	468	1128	1277	2161	3874	2490	635	1336	123	F

transport system. Therefore, broad recommendations emerged out of the study can be written as:

1. Planning should focus on reduction of the traffic load on existing road network through various travel demand management measures.
2. Emphasis should be placed improving public transportation system.
3. Concerted efforts are needed in removing encroachments, bottlenecks, improving traffic signal, road condition, and geometrics at intersections.

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