Efficiency of Roundabouts as Compared to Traffic Light Controlled Intersections in Urban Road Networks

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ABSTRACT

Evaluating the performance of a multi-lane intersection is important to identify the best scheme as congestion is becoming a worldwide serious problem. A Multi-stream Minimum Acceptable Space (MMAS) Cellular Automata (CA) model is used for the simulation of vehicular traffic at double-lane roundabouts and cross intersection. Comparison is made between roundabouts with traffic light and without traffic light and signalized intersections on the basis of their performance to simplify traffic congestion. Computer simulations are used to propose critical arrival rates to separate between the three mentioned modes to decrease congestion at intersection points.

Keywords: Traffic flow, Roundabout, Throughput, Multi-stream Minimum Acceptable Space, Cellular Automata

1 INTRODUCTION

Nowadays traffic congestion is one of the main societal and economical problems in urban areas related to transportation industries both in developed and developing countries. In the last five decades, a wide range of traffic flow theories and models have been developed to minimize problem of traffic congestion. Traffic congestion is mainly observed around intersections and roundabouts in urban areas. Particularly, it becomes severe during peak hours. Modern roundabouts are beginning to be considered as an alternative traffic control device that can improve safety and operational efficiency at intersections when compared to other conventional intersection controls, usually for traffic flow management or to improve safety (Feng et al., 2007). Modern traffic management depends highly on the efficiency of mechanisms, such as the controlled intersection and multi-lane roundabouts to maximize flow along the system.

Thus, the study of traffic flow on multi-lane roundabouts aims to understand traffic behavior in order to answer the following basic questions: how to manage traffic congestion, what causes congestion, the behavior of drivers' contribution to traffic congestion etc. These factors which could contribute in influencing traffic flow on multi-lane roundabouts and flow in the network need deep investigation. For this reason, understanding what type of flow is occurring in a given situation is helpful to decide the most relevant method for analysis and description of the problem. In addition to this, managing traffic in congested road networks requires a clear understanding of traffic flow operation and causes of congestion.

Greenwood and Bennett (1996) indicated that fuel consumption of a vehicle increases approximately by 30% under heavy congestion. In order to reduce these losses, Shokri, et al. (2009) suggested that it is required to create an efficient method to resolve traffic congestion and reduce the delay time. The dynamic vehicular delay at intersections is a major current concern, because the standard static network equilibrium formulation fails to capture essential features of traffic congestion.

The performance of single and double lane unsignalized, signalized and roundabout intersections have been investigated in Kakooza et al. (2005) in terms of expected number of vehicle and waiting time using simple mathematical modeling. Signalized roundabout means a roundabout which is controlled by a traffic light at the entrance of each arm, whereas unsignalized roundabout is governed by the give-way rule. In the same paper the authors concluded that the performance of signalized intersections is superior under heavy entering traffic volumes while the roundabout performs better under light entering traffic volume in terms of delays. However, no clear-cut was given to qualify what "heavy" and "light" entering traffic volume means. On the other hand, the model does not compare the operational performance of signalized roundabouts, unsignalized roundabouts and signalized intersections under similar traffic density.

Wang and Ruskin (2002) proposed a multi-state cellular automata (CA) ring under the off-side-priority rule to study traffic flow at a single-lane urban roundabout and investigated different properties of single-lane roundabouts. The findings of their research indicated that under given similar topology with fixed arrival and turning rates, the size of the roundabout impacts little on throughput level. They also found that queue formation occurs at densities in the range of 0.2 – 0.8 and it increases as arrival rates increase.

Despite the fact that describing the characteristics of traffic flow is difficult, the rapidly growing volume of vehicular traffic, the cost of construction and the cost of space on which to construct and expand new infrastructure, hazardous environmental impact due to the emission of pollutants, together with unfavorable delays suffered in congested traffic flows are among the basic feature which necessitate the search for new control mechanism and optimal condition for traffic flow on multi-lane roundabouts. For effective planning knowing the performance of each type of setting in designing a facility for an intersection is crucial. To the knowledge of the authors, no effective comparison was made in the performance of roundabout with and without traffic light and a cross intersection with traffic signal.

In this paper, we will discuss the operational performances of roundabouts and intersections and recommend the best design of double lane intersections depending on the average arrival rates. This paper is organized as follows. In section 2 modeling a double-lane roundabout have been presented. In section 3 model description and computational techniques were introduced. Section 4 contains simulation results of the comparison made between roundabout with and without traffic light, and a signalized cross intersection. Finally, we close the paper with a concluding remark in Section 5.

2. MODELING DOUBLE-LANE ROUNDABOUT USING CA MODEL

A roundabout in its design may have three, four, five or more incoming and outgoing flow directions on which traffic can flow. These flow directions are commonly called arms of the roundabout. But in some countries the most frequent ones are roundabouts with four arms. A roundabout may be a single-lane, double-lane or three-lane. If it is a double-lane, its circulatory roadway must also be of a double-lane and its arms must have at least two-lanes. The same is true for the single- and three-lane roundabouts. In a single-lane roundabout only a single vehicle can enter to the roundabout at a time; others wait at the yield line one after the other. But in a double-lane roundabout two vehicles can approach a roundabout at a time. This is the major difference that exists between roundabouts.

Modern roundabouts have deflection for the entering traffic usually in the form of raised islands (splitter islands) at entry and a raised central island (Wang and Ruskin, 2002, 2006; Wang et al., 2005).The splitter islands direct traffic toward the central island, which further deflects vehicles to the right. Deflection results in lower speeds and improved safety. According to the give way rule, vehicles from the entry roads of a roundabout give way to those vehicles already circulating on the roundabout. All entering vehicles on the approaches have to evaluate a gap in the circulating flow before entering the circulating traffic.

With these entire features, a roundabout has some advantages in comparison to signalized intersection such as yield-at-entry operation, fewer conflict points, allowing more time for drivers to react while reducing crash severity, and vehicles travel in the same direction virtually eliminating the possibility of right angle or head-on collision. Multi-lane roundabouts are a next-step urban traffic alternative in situations where single-lane roundabouts prove inadequate (Robinson et al.,2000).

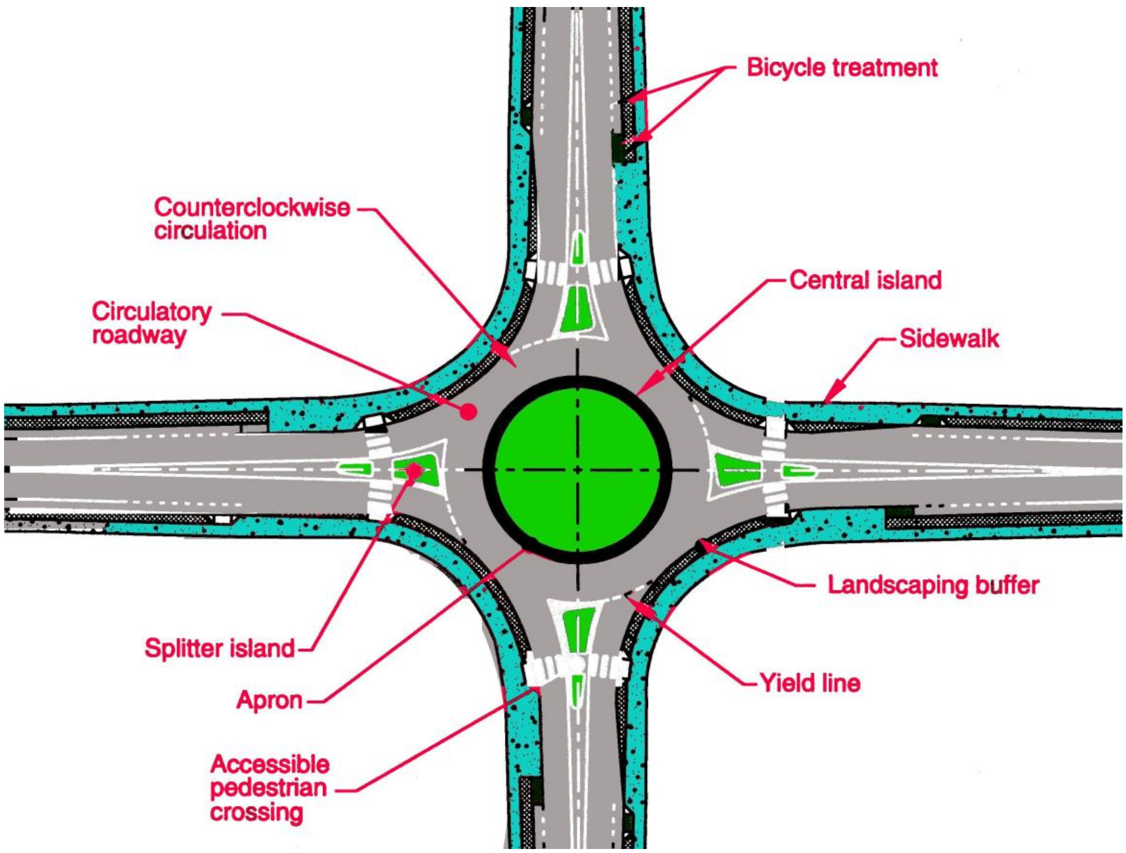

Figure 1. A roundabout with four arms describing the physical geometric design (from Robinson et al., 2000).

2.1. Cellular Automata (CA) Model for Double-lane Roundabout

Cellular Automata model is a model that is applied in dynamical systems with space, time and system states are assumed to be discrete variables. In this model the road is divided into sections of a certain equal length Δx and the time is discretized to equal time steps of Δt.

The CA model describes the traffic system as a lattice of cells of equal size, which is typically the average length of road occupied by one vehicle. The sizes of the cells are chosen so that the speed of a vehicle is equal to one move to the next downstream cell during one time step. The vehicle's speed can only assume a limited number of discrete values ranging from zero to $v_{\max}$. The variables describing phases of each site are updated for every time step. The variables are the speeds of the vehicles, indicating whether the cells of the lattice are occupied or empty or any other parameters, which describe an aspect of traffic flow. The state of a cellular automaton depends on the value of discrete variable(s) at each site. Each road section can either be occupied by a vehicle or is empty and the dynamics are given by update rule as discussed below.

2.1.1. The Update Rule

The update rule can be expressed in terms of the sequential cells. If there is a vacant cell in front of the cell occupied by a vehicle, the vehicle will move forward one cell in the current time step. If the cell at the front is also occupied, the vehicle will stop there in that time step. The state c^{t+1}ofthe n$^{\text{th}}$ cell in the next time step is decided by the states of its own cell c_n^t, the state of the cell in front and the cell behind in this time step, where t and n express time and position sequence respectively. The states can only be 0 or 1, where 0 means the cell is vacant and 1 means it is occupied by a car. Therefore, the update rule can be expressed as follows:

- If $c_n^t = 1$ and $c_{n+1}^t = 0,$ then $c_n^{t+1} = 0$ and $c_{n+1}^{t+1} = 1$
- If $c_n^t = 0$ and $c_{n+1}^t = 0,$ then $c_{n+1}^{t+1} = 1$
- If $c_n^t = 1$ and $c_{n+1}^t = 1,$ then $c_{n+1}^{t+1} = 1$

Although cellular automaton models lack the accuracy of the time-continuous like car-following models, they still have the ability to reproduce a wide range of traffic phenomena. Due to the simplicity of the models, they are numerically very efficient and can be used to simulate large road networks in real time or even faster. Thus, it is used to model multi-lane roundabout. A double-lane roundabout in this model consists of a regular grid of cells, each in one of a finite number of states, such as “On” and “Off”. The grid can be in any finite number of dimensions; in our case it has a dimension of length. For each cell, a set of cells called its neighborhood (usually including the cell itself) is defined relative to the specified cell. An initial state (time $t = 0$) is selected by assigning a state for each cell and a new generation is created (advancing t by 1), according to the priority rule discussed under Section 3.3, that determines the new state of each cell in terms of the current state of the cell and the states of the cells in its neighborhood. We developed a multi-state CA rings in order to characterize vehicles' dynamics. The rings are sectioned into cells so that the number of cells in the ring is determined by the real dimension of the roundabout. If real dimensions of the roundabout are known, then the number of cells in each ring will be known by using the following simple mathematical formula.

$$number\ of\ cells \cong \frac{perimeter\ of\ the\ ring}{length\ of\ a\ cell} \quad \ldots\ldots 2.1$$

The state in each cell has two physical meanings. If $c_i = 0$, it means that there is no vehicle in this cell. If $c_i = 1$, it means that here is a vehicle in this cell. The waiting vehicle looks at the cell in front of the yield line and/or the cell(s) behind it, that is located at the arm from which the vehicle is waiting to enter according to the appropriate gap it needs. Each cell corresponds to an average size of a vehicle and each vehicle moves forward only if it gets a vacant space in front of it. Vehicles on single and double-lane roundabouts are assumed to obey the same give-way rule (the priority rule). Priority-sharing or give-way rules can also be replaced by fixed waiting periods determined by traffic light cycles or human interventions.

2.2. Driving Principle on a Roundabout

Unlike traffic light controlled intersections, roundabouts in general are governed by the priority rule. According to this rule, vehicles waiting to enter a roundabout must give way to vehicles already on the roundabout and vehicles exiting from the inner lane of multi-lane roundabouts additionally have priority over vehicles rotating on the outer lanes of the rotary of the roundabout. A vehicle arrived at the entrance road of a roundabout at either arm will not be allowed to change lane after it entered the roundabout entry road, usually 100 meters away from the roundabout entrance. Thus, the vehicle is assumed to be in its lane as it entered to the entry road, either at the right lane or left lane depending on the preference of its destination. As soon as vehicles arrived at the yield line of the entrance of the roundabout at either arm and at either lane, under the offside-priority rule, the vehicles stop and wait at a roundabout entrance by giving way to the vehicles already on the roundabout until they get an appropriate gap (cell number).

Once the vehicle is entered to the roundabout rotary road, it makes a turning maneuver around the central island until it exits from the roundabout. Think of a vehicle on the inner lane of the roundabout rotary that is about to exit at the next arm, since it has a priority over the vehicle on the outer lane of the rotary, this vehicle communicates with a vehicle on the outer lane of the rotary road whenever it wants to exit from the roundabout by giving a sign for the vehicle on the outer lane which is an indication that the vehicle wants to exit from the roundabout at the next arm. As soon as this sign is received by a vehicle on the outer lane of the roundabout it gives way to that vehicle by stopping where it was. Consequently, vehicles on the outer lane and behind the vehicle by which the message is received will be delayed unless there is a significant gap in front of those vehicles so that the vehicle may not be forced to decelerate and come to stop. It is only this rule and the geometry of the roundabout that enables traffic to flow on the roundabout smoothly.

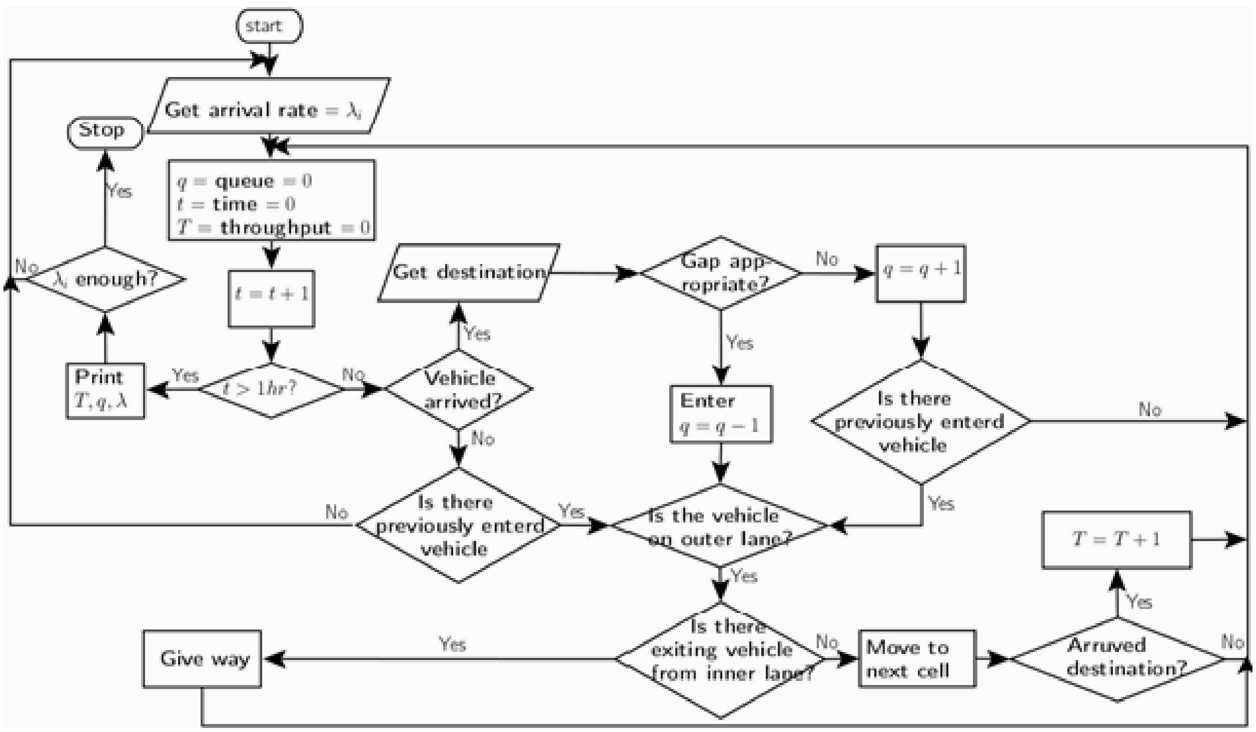

Figure 2.Flowchart of the program used for the simulation.

3.1. Vehicles' Arrival at the Entrance Road of a Roundabout

The mean arrival rate is the rate at which vehicles arrive at the entrance road of the roundabout. Mean arrival rate, denoted by λ, is the total number of vehicles, denoted by *N*, that arrived within some interval of time,*Δt*, divided by *Δt*. Mathematically,

$$\lambda = \frac{N}{\Delta t} \quad \ldots\ldots 3.1$$

Usually it is given in unit of vehicle per second *(vps).* It describes how many vehicles arrived at the entrance road of a roundabout per second. And the arrival rate is determined using equation (3.1) and it can be related to the density ρ, by the following equation:

$$\rho = \frac{\lambda \Delta t}{\Delta l}, \quad \ldots\ldots 3.2$$

Where, Δl is the length of a section of road on which vehicles are distributed during the interval of time Δt.

It is impossible to exactly forecast the time when vehicles arrive at the entrance road of a roundabout because of the random nature of vehicles' arrival at the entrance road, but using Poisson probability distribution it is possible to approximate vehicles' arrival rate.

A queue occurs when instantaneous demand exceeds instantaneous capacity of the road intersection. The queue-length depends on the inter-arrival times and service processes. The service process here means all stages of the vehicle arriving at the end of the queue and crossing the intersections (hence leaving the queue). Queuing models are characterized by the distribution of inter-arrival times and the distribution of the service times. Two distributions are normally used, Poisson or general distribution (Wang, 2003). In this paper we used the Poisson distribution because the random variable, in our case the number of arrivals (number of vehicles), is a discrete variable.

The form of the Poisson distribution is given by equation (3.3).

$$P(r) = \frac{(\lambda\Delta t)^r e^{-\lambda\Delta t}}{r!}, \quad \ldots\ldots 3.3$$

Where $P(r)$ = probability of arrival of r vehicles in any interval of Δt seconds,

λ = average rate of arrival,

r = number of vehicles expected to arrive during Δttime interval,

Δt = time interval in which r vehicles are expected to arrive.

Equation (3.3) is used to find the probability of $0, 1, 2, \ldots, v - 1$ or v arrivals, for $v \in W$ (set of whole numbers), only during the specific arrival rate of λ. In this paper we analyzed traffic behavior during different arrival rates. Thus, we used equation (3.1) to get equation (3.4) in order to have different arrival rates. Suppose we have N vehicles counted during some hours of the day. And let N is divided into $N_1, N_2, N_3, \ldots, N_i, \ldots, N_k$ subdivision of observations such that N_i is the number of vehicles counted between $i - 1$ and i hours. And $N_i \neq N_j, \forall i, j \leq k$. Then, we can calculate the$k$ arrival rates using equation (3.4).

$$\lambda_i = \frac{N_i}{\Delta t} \quad \ldots\ldots 3.4$$

Further, using equation (3.4), we can rewrite equation (3.3) as follows.

$$P_i(r) = \frac{(\lambda_i\Delta t)^r e^{-\lambda_i\Delta t}}{r!} \quad \ldots\ldots 3.5$$

Thus, the distribution ofthe arrival of vehicles is calculated using equation (3.5). We assumed that vehicles arrival rates at each arm of the roundabout are equal as the operational performance of a roundabout is improved when arrival rates are balanced (see Fig 4).

3.2. Predetermined destination

Drivers take their destination into account before they enter into the roundabout entry road. A four arm roundabout has four entry and four exit directions. A vehicle that entered to a roundabout has four possible exit directions (vehicle's destination). It either turn right, left, make a u-turn or drive straight through the roundabout. Therefore, it is quite logical to assume that drivers' turning direction is predetermined at their entry. According to this assumption, we allocate a lane to each arrived vehicle depending on its destination. The vehicles arrive at the yield-line by moving ahead one cell at each time step either on the right or left lane of the entry road according to the lane pre-allocated for it. It is usually hard and time consuming for vehicles in the inner lane to go out of the roundabout and follow its exit direction as they should get a free cell in the outer lane. Therefore, it is assumed that vehicles on the right lane of the entry road are either turning right or drive straight through the roundabout. In the geometry of many of the roundabouts, extra right-exits are designed (not part of the roundabout)to give easy access to vehicles turning right. But few may still use the roundabout’s right exit. So, 25% of the vehicles on the right lane are assumed to turn right. And the rest 75% drive straight through the roundabout. In the same way, 25% of the vehicles on the left lane of the entry road make a u-turn because only some of the vehicles on the left lane are usually observed making a u-turn, while the rest 75% taken to be left-turning.

3.3. Lane Allocation

In two lane roundabout, approaching vehicles take either of the two lanes of the entry road depending on their turning preferences. Lane is allocated randomly to a vehicle arrived at the entrance road of a roundabout with equal probability of joining either of the two lanes and the vehicle's turning rate is determined at the start of the entrance road of the roundabout according to their predetermined destination. It is assumed again that vehicles are not allowed to change lane once they entered the entrance road of the roundabout until they exit from the system. Because changing lane on both the approach and within the roundabout in general is less likely observed or may be considered as abnormal.

3.4. Entry to the Roundabout

A vehicle arrived at the yield line at either lane, will be assigned a probability to which direction it is to exit from the roundabout with the number of cells it traverses. Having this assignment it waits at the yield line until it gets an appropriate gap that enables it to enter into the roundabout facility. Thus, it needs to check an appropriate gap depending on its driver's behavior to enter into the roundabout.

3.4.1. The Multi-stream Minimum Acceptable Space (MMAS)

As briefly outlined by Wang and Ruskin (2002), the MAP method categorizes the driver's behavior into four groups (radical, urgent, moderate and conservative). A double-lane roundabout is used to illustrate the MMAS method in figure 3 for different drivers that are assigned to a different cell number between rotating vehicles to enter into the roundabout.

In order to discuss vehicle's entry into the roundabout two CA-rings, having different diameter and partitioned into unequal number of cells as shown in Fig. 3, have been used. The outer ring has 28 cells and the inner one has 22 cells. Let C_{out} and C_{in} be row matricesrepresenting the outer ring and inner ring cells. To each cell a sequential number is assigned starting from 1 in figure 3 as follows:

$$C_{out}(1) = 1,\ C_{out}(2) = 2,\ \ldots\ C_{out}(i) = i,\ \ldots\ C_{out}(28) = 28.$$

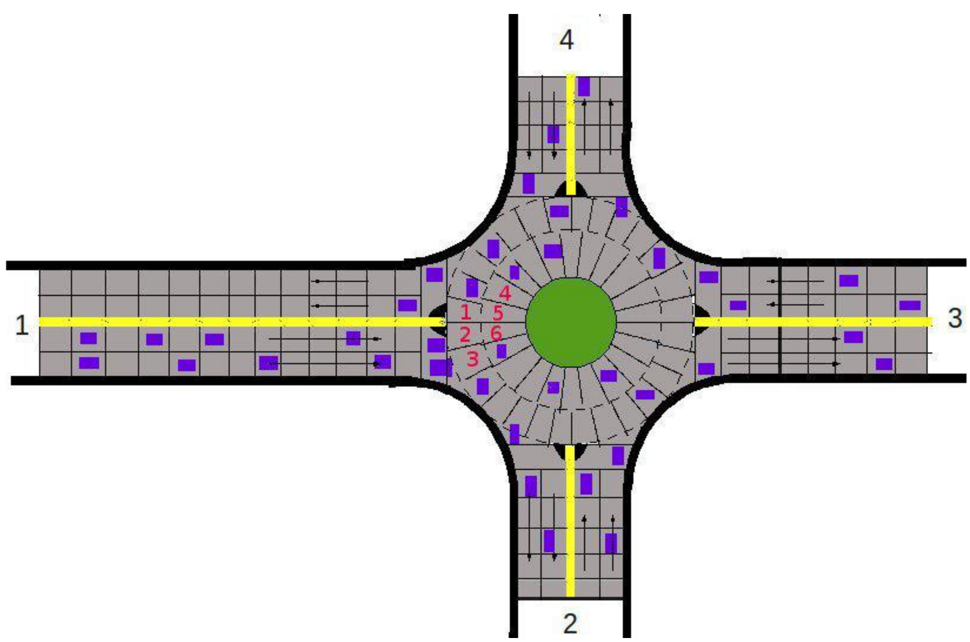

Figure 3. Demonstration of vehicles' entry to roundabout.

Suppose a vehicle is arrived at the yield line from the right lane at time step *t*. If its driver is with the radical behavior, it needs to check whether at least $C_{out}(1)$ and $C_{in}(4)$ are vacant at time step *t*, so as cells $C_{out}(2)$ and $C_{in}(5)$ will be vacant at time step *t+1*. Hence, the vehicle enters to the roundabout via $C_{out}(2)$ at time step *t+1*. By the time step *t+2* cell $C_{in}(6)$ will be vacant. Thus, the vehicle will move to it at that time and starts its journey on the inner lane of the rotary of the roundabout. Moreover, if there is a vehicle on $C_{out}(1)$ at time step *t+1*, the vehicle is forced to decelerate to maintain the gap between them. As a result, the vehicle will be delayed for the next two time steps, $t + 2$ and $t + 3$, because the entering vehicle will cross the front cell diagonally and occupies two cells at a time. This delay may generate gridlock (Wang and Ruskin, 2002), but the formation of gridlock is not included in this paper since the gap is maintained. This delay is assumed to continue to every vehicle on the consecutive cells behind, unless there is at least one vacant cell so that the delay will be removed as the vehicle on the cell behind the vacant cell can occupy the vacant cell. Else if the driver is with the urgent behavior, this vehicle requires a 2-cell space both on the outer and inner ring of the roundabout to enter to the facility. In the same way as the radical one, it causes a delay to the behind vehicle but the delay is only for one time step. Likewise, the moderate and conservative behaviors need 3-cells and 4-cells space both on the outer and inner rings of the roundabout rotary respectively; but both of these behaviors are not expected to cause any delay on the vehicles rotating behind as there is enough gap between the entered vehicle and the vehicles rotating in front and behind the entered vehicle.

It is all the same for the vehicle arrived at the yield line from the right lane of the entry road except that the vehicle to enter needs to check only for the space on the outer ring and the vehicle entered will navigate the roundabout according to the driving principle described under Section 2.2. Here, only entry via arm 1 is discussed. Note that the same procedure will apply for entries via the rest of the arms. Finally, all entries through the arms must be taken into consideration because a vehicle entered from arm 1 for example may exit via arm 3 and since it passes in front of arm 2. Thus, it affects a vehicle that enters via arm 2.

3.5. Navigation on the Roundabout

As soon as the vehicle entered into the roundabout it starts its navigation without stopping on the roundabout, except for the reason discussed under Section 2.2, for which a straight through vehicle on the outer ring yields for the exiting vehicle from the inner ring in the next time step.

Otherwise, each entered vehicles move one cell for each time steps until they exit from the roundabout at their destination according to the update rule discussed in Subsection 2.1.1.

3.6. Exits from the Roundabout

Once a vehicle's turning direction is identified, the number of cells it traverses will be known before entering into the roundabout. Then, the vehicle enters into the roundabout after getting the appropriate gap (the required cell number) with an appropriate number of cells (the distance that it needs to travel according to its turning directions). The number of cells assigned to the vehicle is equal to the number of cells that the entered vehicle has to traverse to arrive at its destination exit. If the entered vehicle completes all the cells given to it by moving one cell at each time step according to the update rule the vehicle exits from the roundabout. The exited vehicle will be added to the throughput. This is determined by the Multi-stream Minimum Acceptable Space method described under Subsection 3.4.1.

Vehicles entered a roundabout will arrive at their destination after some time by traversing a quadrant or quadrants of the roundabout. When a single vehicle exits from the roundabout, it leaves one cell empty because in the assumption a vehicle moves a cell at a time. The cell left by an existing vehicle at time t may or may not be occupied at time $t+1$, but at this time the next cell must be empty because the exiting vehicle moved to the exiting road of the roundabout. At the time this is done, the next vehicle will accelerate at the next time step so that the empty cell will be occupied leaving a gap behind. The gap will be accumulated at the next arm of the roundabout which helps the waiting vehicles enter the roundabout as long as it is appropriate for the driver's behavior. Otherwise it continues to be accumulated in the same way until an entering vehicle occupies at the other arm. This is very important for the study of the traffic situation at a roundabout.

4 SIMULATIONS AND DISCUSSION

4.1. Assumptions

In the simulation, double-lane roundabout with 4 arms whose radius of the central island is 11 meters with lane width of 3.7 meters each is considered with the following assumptions.

1. One cell is equivalent to approximately 4.17 meters. This figure is an average length of a vehicle. In this case large vehicles like buses and small trucks occupy three and two cells

respectively; whereas personal cars occupy a cell. By the geometry specified above, the inner lane of the roundabout has 22 cells whereas the outer lane has 28 cells.

2. Vehicles' speed is 30km/h, 39.615km/h and 50.04km/h on the roundabout without traffic light, roundabout with traffic light and cross-intersection with traffic light respectively. Hence, a vehicle enters and rotates the roundabout without traffic light with a speed of 30km/h. This is because vehicles on the rotary road need to check vehicles that entered from another arm. And the facility forces the vehicles to slow down since it is circular. This creates speed reduction as an overall effect. That is why 30km/h is taken as an average speed of vehicles rotating on the roundabout without traffic light. With this speed a vehicle needs approximately 0.5 seconds to traverse a cell. For the Roundabout with traffic light, however, 37.53km/h is taken. This is because flow is only from a single arm. Thus, there are no vehicles from another arm that interrupt their navigation on this facility. In the same way 50.04km/h is taken as an average speed of a vehicle crossing a cross intersection with traffic light. Vehicles on this facility simply start from where they stopped with this speed as the facility has less effect on their speed.
3. The length of the entry road is taken to be 24 cells (approximately 100 meters). It is a road section where vehicles wait to enter to the roundabout.

The variables of our study are arrival rate, queue-length and throughput. Of which throughput and queue-length are dependent variables as both of them are observed to depend on the arrival rate. Whereas the proportion of each of the four types of drivers behaviors are parameters of the study that needs to be approximated from a field data. As a result, the relationship between the variables and parameters are experimented with each other and within themselves.

In the study, we compared roundabout's performance when it is controlled by traffic signal and when it is made to operate as usual by the self organized rule; in order to identify the optimal mechanism in terms of performance. The problem is formulated as in the flowchart (Fig. 2) and is implemented (using FORTRAN code) that all realities like the random nature of traffic flow, the priority or give way rule that drivers follow while driving through roundabout and traffic light color changes that used to permit traffic to flow or to deny. And the output is simulated in graphical form.

4.2. Results and Discussion

4.2.1. Throughput versus Different Arrival Rates at Arms of a Roundabout

In reality traffic demand at arms of the roundabout is rarely equal. Thus, we found that it is important to discuss the effect of unbalanced traffic volume at the entrance road of a roundabout on its operational performance.

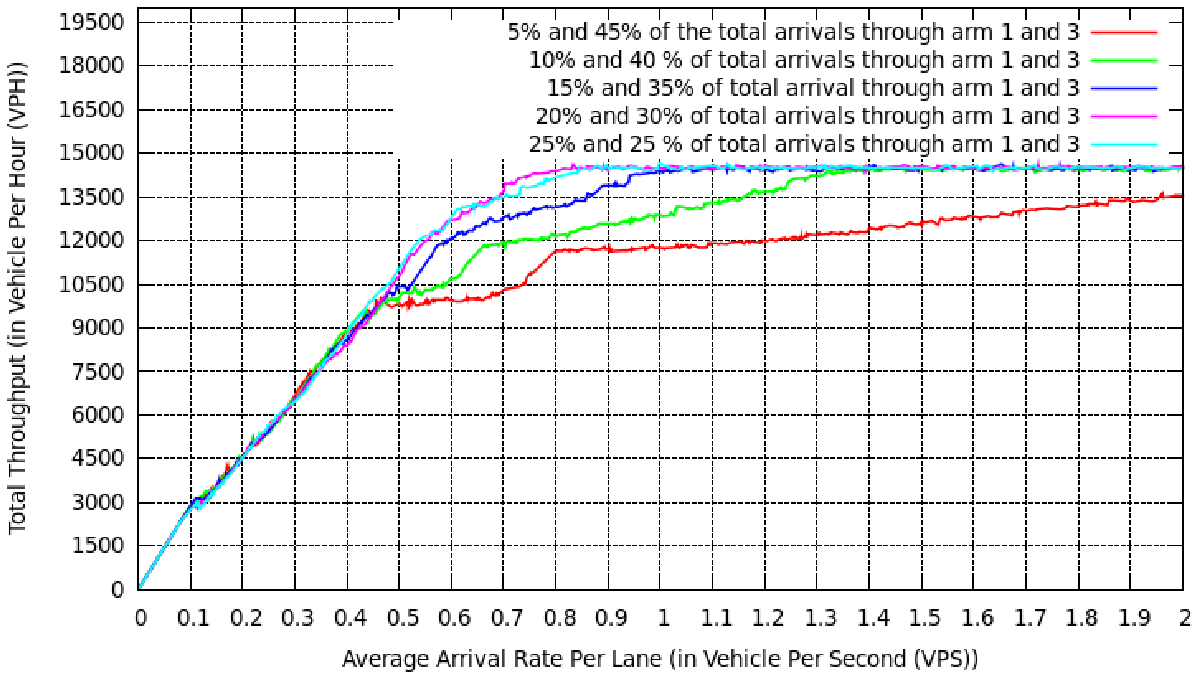

Figure 4. The effect of unbalanced traffic flow at the entrance of a double-lane roundabout. This figure shows the effect of unbalanced traffic volume at entrance road of a roundabout on performance. In this figure traffic volume at arms 2 and 4 are assumed to be each 25% of the total. The rest 50% is distributed unequally to arms 1 and 3 as indicated in the legend.

By keeping vehicles arrival at opposite arms 2 and 3 of the roundabout to be 25% each (of the total arrival) and if the distribution of vehicles on arm 1 and 3 are varied until they are equal, the performance of the roundabout will not be affected up to the average arrival rate of approximately 0.475 vps (the arrival of 19 vehicles in every 40 seconds) (see Fig. 4). When the arrival rate is approximately greater than 0.475, however, the throughput will be affected. For instance, when 5% of the total arrivals is at arm 1 and the rest 45% is at arm 3, the throughput is smaller by more than 1000 vehicles compared to when it is 10% and 30% at arm 1 and 3 respectively.

As it can be deduced from figure 4, the throughput is maximum when traffic density is approximately equal at each arm. However, as the traffic volume gets unbalanced the throughput is getting reduced. One of the reasons for this is that vehicles at the entrance where traffic density is high get more chance than those at the arm where traffic density is low. Thus, vehicles from the arm with high density enter to the facility one after the other forming platoons. As a result, vehicles from the arm with low density wait for a long time forming a queue. In the subsequent subsections, we have used the maximum throughput to compare the performance of a roundabout with other intersection designs (cross intersection) to be logical.

4.2.2. Comparison of Roundabout with and without traffic light

Roundabout with traffic light is a roundabout having a traffic light installed at each entrance of the roundabout as a control mechanism like any intersection controlled by traffic light that is to be operated either at a full time basis or at a part time basis. Traffic light that is installed at a full time basis is used to regulate traffic throughout the day; whereas that of a part time basis assumed to be used to regulate traffic during some time of a day particularly when traffic density is high. The basic question expected to be answered by this study is: which control mechanism is optimal in terms of performance. The result is actually as described below.

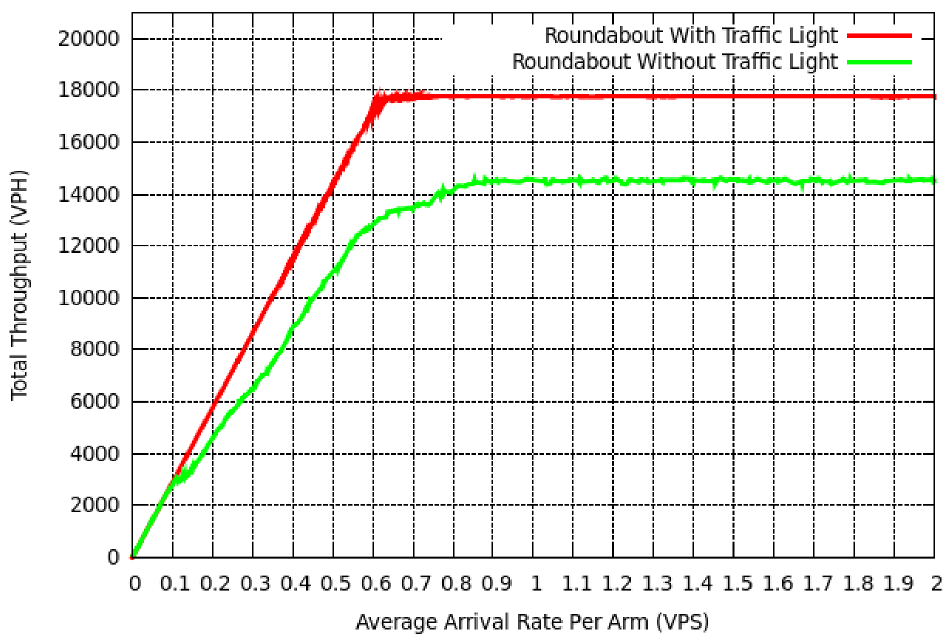

Figure 5. Comparison of roundabouts with and without traffic light. The figure shows the comparison of roundabout with and without traffic light. In the simulation the light is assumed to be red for 40 seconds and green for 20 seconds. Theyellow time is assumed to be 2 seconds. All other assumptions discussed in this paper also hold true.

Figure 5 shows that the optimal performance is achieved when traffic light signal is installed at the entrance road of the roundabout as a control mechanism. From the figure 5, when traffic density is light specifically when the arrival rate is approximately less than 0.1 vps (i.e. the arrival of 1 vehicles every 10 seconds on each lane), it is better to use roundabout without traffic light especially when the electric power consumption, fuel consumption and emission by the vehicles stopped by red light at the entrance of signalized intersection are taken into consideration. When traffic density exceeds this value, however, it is recommended for the traffic to be regulated with traffic light at a part time basis as large queues started to build during these arrival rates. Thus, 0.1 vps is a critical arrival rate for a double-lane roundabout without traffic light.

4.2.3. Comparison of Roundabout with signalized cross intersection

The other scenario that needs to be considered is the case when the roundabout is totally removed and substituted by a signalized cross intersection. The frequently used measures of the effectiveness of signalized intersections are the mean delay, length of queue, and number of stops (Sadoun, 2003). But here the average length of queue formed at each arm is used as a measure of effectiveness by varying the arrival rate at which the optimal throughput is obtained. As the graph in figure6 describes the performance of the roundabout with traffic light and the cross intersection have exactly the same efficiency level when traffic density is light; i.e. when the arrival rate is approximately below 0.64 vps (which corresponds to about 16 vehicles per each 25 seconds). Thus, with this arrival rate, roundabout with traffic light is optimal in terms of accident reduction as speed is highly reduced in roundabouts. Otherwise when traffic density is above 0.64 vps cross intersection is far better.

In the same way, the comparisons of the three mechanisms are shown in figure 6. As it can be seen from the figure, the three mechanisms have shown almost the same performance when the arrival rate is approximately below 0.1 vps (one vehicle in every 10 seconds). In contrary when the average arrival rate is above 0.1 vps per lane, roundabout without traffic light is inefficient to be used. When the arrival rate at the intersection is above 0.64 vps per lane the roundabout must be removed and substituted with cross intersection controlled with traffic light, as this will result in more than 5,000 vehicles difference in throughput within an hour, which will otherwise form a queue.

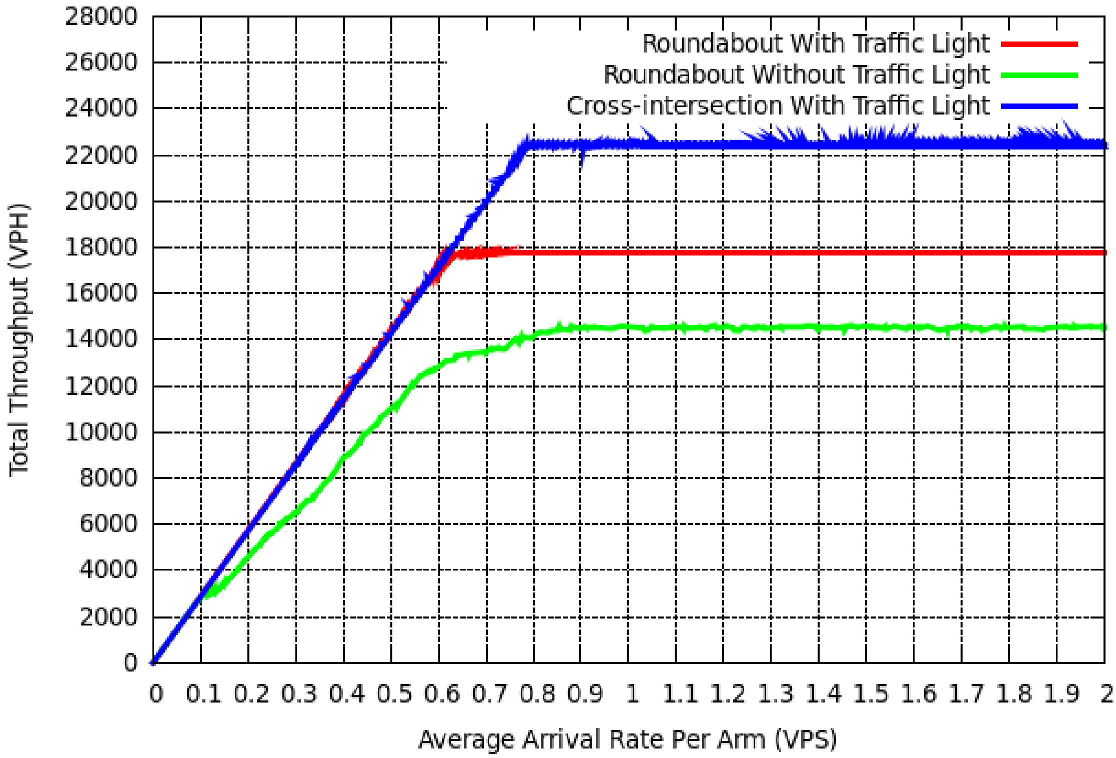

Figure 6. Comparison of roundabout without traffic light, roundabout with traffic light and cross intersection. The figure shows the comparison of roundabout with traffic light and cross intersection. In the simulation the light is assumed to be red for 40 seconds and green for 20 seconds. The yellow time is assumed to be 2 seconds. Every other assumption discussed in this paper also hold true.

Thus, when traffic is greater than this arrival rate, the order of decreasing in performance is given as: cross intersection, roundabout with traffic light and roundabout without traffic light. We can also view this comparison in terms of the queue length formed at the entrance of an intersection due to the inflow dynamics.

In terms of queue length, all the three mechanisms are approximately at the same level when the arrival rate is nearly below 0.1 vps. However, when the arrival rate is greater than 0.1vps, in the case of roundabout without traffic light queue starts to pile up while roundabout with traffic light and cross intersection with traffic light remain at the same level till the arrival rate is approximately 0.64 vps. As indicated in figure 7, when roundabout with traffic light is employed queue length starts increasing as the arrival rate exceeds approximately 0.64vps; whereas, in the case of cross intersection with traffic light queue length begins to buildup at about 0.78vps.

In general, from this study we can conclude that, un-signalized roundabout performs least as compared to a roundabout with traffic light and cross intersection with traffic light signal. If we want to increase the operational performance of intersections at high density (more than 0.64 vps per lane on average) double lane roads, then they have to be substituted by cross intersections controlled by traffic light signals by totally removing the roundabout not by a roundabout with traffic light as the aim is to optimize their operation.

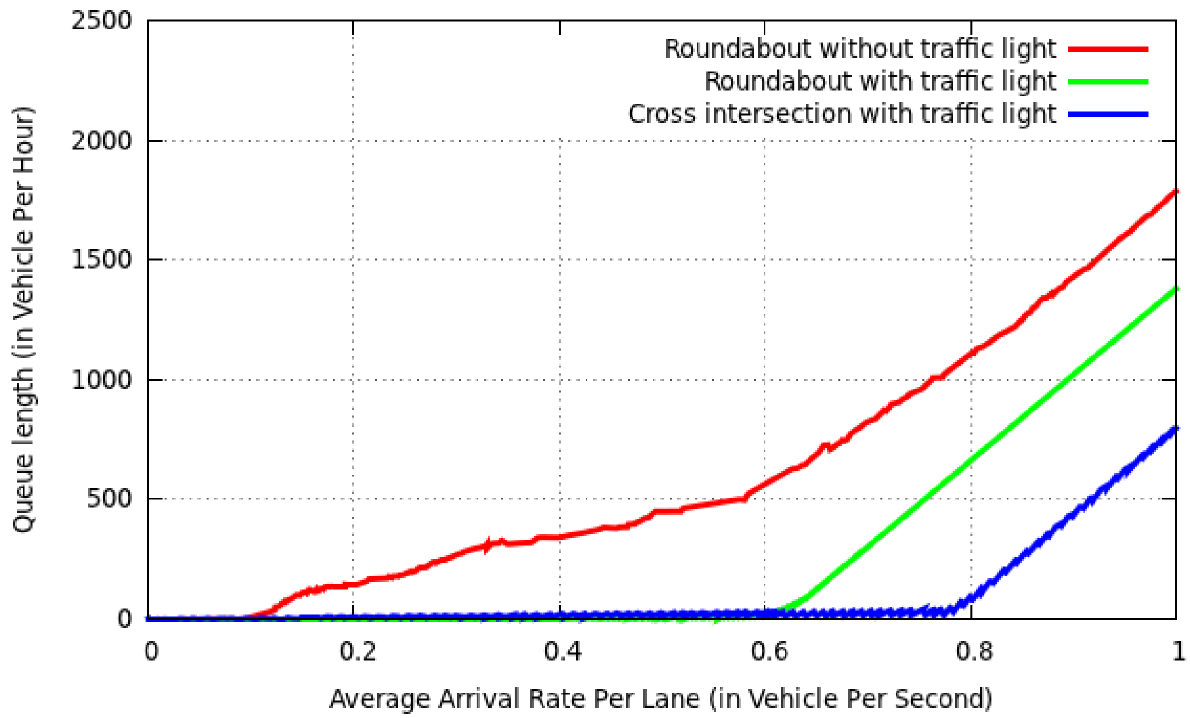

Figure 7. Comparison of the management of Intersection in terms of the queue length formed. The figure shows the comparison of roundabout with traffic light and cross intersection in terms of the queue length formed. Every other assumption discussed in figure 6 also hold true.

5 CONCLUSION

Though modeling multi-lane roundabout is a complex activity due to drivers' behavior and vehicle-to-vehicle interaction, Cellular Automata model can successfully catch these parameters in a better detail. The measures of performance: arrival rates, throughput and queue length can give adequate information to determine the roundabouts operation and help to decide on traffic plan at intersections.

Roundabout without traffic light performs best when the arrival load is evenly distributed on each arm of the intersection; and the more unbalanced the arrival rates are at each arm of the roundabout, the less it performs and hence the longer queue on the road near to the intersection is to built. Roundabout with traffic light is operationally better than roundabout without traffic light installed at its entrance. However, for arrival rates below 0.1 vps, its performance is exactly the same when traffic light is absent. The average critical arrival rate for the best performance of a roundabout with traffic light is approximately 0.64 vps per lane provided there is equal distribution of arrivals per each arm. Below this arrival rate roundabout with traffic light is found to be efficient. However, when arrival rates exceed this critical value, its performance is compromised and a queue starts to build. Thus, a cross intersection with traffic light is a better choice than a roundabout if the average arrival rate per each lane exceeds about 0.64 vps which means an arrival rate of nearly 16 vehicles per each 25 seconds. The average critical arrival rate for a double-lane cross intersection is approximately 0.8 vps per lane. Thus, during peak hours the trend that traffic officers are intervening to regulate traffic is an alternative solution to minimize congestion.

In designing intersection facilities with double-lane urban road networks, if traffic density is low (i.e. below 0.1 vps per lane on average) roundabouts are preferable due to their low operational costs as well as in improving safety. But in this study it is found that cross intersection with traffic light installed is the best in performance. Thus, to have optimal operational performance where traffic density is high, greater than 0.64 vps, roundabouts have to be removed and substituted with cross intersections. Where the average arrival rates are below 0.64 vps per lane, however, installing traffic light signals at the entrance of the roundabout to operate at part-time basis is enough to have smooth traffic flow. In contrary, unsignalized double-lane roundabouts are no more recommended where the arrival rates are observed to exceed 0.1 vps per lane as queue start to buildup otherwise. Thus, in a roundabout with traffic light is the traffic light recommended to be initialized when the arrival rate is above 0.1 vps. As a natural extension of this recommendation one can investigate the economic impact (cost analysis) to remove and substitute with cross intersections. In addition to this, comparing the impacts of pedestrians on the operational performances of roundabouts and intersections needs further investigation.

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