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# Effects of Driver Behavior on Traffic Flow at Three-lane Roundabouts

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*Abstract-* **This paper proposes Multi-stream Minimum Acceptable Space (MMAS) Cellular Automata (CA) models to simulate driver behavior and its effects on traffic flow at three-lane roundabouts. Using cellular automata, the models are developed by modeling the detailed space considerations for drivers entering *un-signalized* three-lane roundabouts. Heterogeneity and inconsistency of driver behavior and interactions at entrances of three-lane roundabouts are simulated by incorporation of different categories of driver behavior and reassignment of categories with given probabilities at each time step. The models are able to reproduce many features of traffic flow at roundabouts for which gap-acceptance models are less appropriate. Various properties of traffic flow at three-lane roundabouts have been explored including throughput, turning rates, critical arrival rates and congestion on roundabouts. Vehicle movements in this paper relate to left-side driving, such as in Australia, New Zealand and Ireland. However, rules are generally applicable.**

*Index Terms*—**Traffic flow modeling, and cellular automata**

## 1. INTRODUCTION

Modeling traffic flow at three-lane roundabouts is a challenging task. In particular, the heterogeneous nature of human behavior, random interactions among drivers, highly non-linear dynamics and large dimensions of the system under investigation are combined together to create considerable complexity.

Three-lane roundabouts are widely used in New Zealand and China. They are used as a next-step alternative in situations where single and two lane roundabouts prove inadequate. However, previous research on modeling roundabouts has mainly focused on single-lanes. Clearly, modeling traffic flow at three-lane roundabouts is more complicated than at single-lanes. In this paper, we focus predominately on driver behavior at entrances and exits of a three-lane roundabout and on the roundabout itself.

Gap-acceptance models have been widely used in modeling traffic flow at the entrances of roundabouts and intersections [18]. Obviously, treating the entrances of roundabouts similar to the entrances of intersections would not reveal the operational characteristics of roundabouts. Other than the limitations of gap-acceptance models discussed in section 2, one major limitation is that these models lack scalability. In other words, they can be used in an individual entrance, but it is difficult to use them in modeling the entire roundabouts or traffic networks.

Cellular automata (CA) models provide an efficient alternative for modeling traffic flow for highway and urban networks [11, 4, 23, 25]. Cellular automaton traffic flow models divide the roads that vehicles drive on into a finite uniform lattice (cells). The variables describing the state of each cell are updated in each time step. The variables may be the speeds of the vehicles in the cells, or the indications of whether the cells in the lattice are occupied or empty, or other parameters that describe different aspects of traffic flow properties. The state of a cellular automaton depends on the values of discrete variables in each cell. Each cell may have a finite number of discrete variables, but only one value of a variable in any single time step.

CA models, incorporating the Minimum Acceptance sPace (MAP) method proposed in [15, 24, 25], can be designed to describe heterogeneous and inconsistent driver behavior and stochastic interaction among individual vehicles. Unlike gap-acceptance models, the MAP method is independent of headway distribution considerations. As such it can be applied to most traffic flow [15, 24].

Performance measurements for roundabouts include throughput (the maximum number of vehicles that can navigate a roundabout), queue lengths and waiting time. Although our models are able to determine all these performance measurements, in this paper, we mainly study the throughput, which can give us an integrated picture of the performance of roundabouts.

## 2. BACKGROUND

A common deficiency of all previous models studying multi-lane traffic flow is the assumption that drivers are consistent and homogeneous. In reality, drivers are heterogeneous and inconsistent. Therefore, it is necessary to develop new models to overcome this drawback and this is a principal focus of much of the work described here.

Gap-acceptance models have long been used in modeling crossing traffic flows at the entrances of roundabouts and intersections. The models are primarily used for single-lane roundabouts or intersections.

Research on multi-stream traffic flow has focused on the estimation of critical gaps in multi-major streams [5, 6, 9]. The EM algorithm [3] has been used for estimating the critical gaps in T-junctions (with two major streams) [5].

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Basically, the method is to observe/measure the rejected and accepted gaps in only one major lane when gaps in other major lanes are so large that these could not influence drivers on a minor stream [5, 6].

Gap-acceptance models assume that a driver enters an intersection when a safe opportunity or “gap” occurs in the traffic. *Gaps* are measured in time and correspond to headway (defined as distance divided by speed). Critical gap and follow-up time are the two key parameters, where *critical gap* is defined as the minimum time interval required for one minor-stream vehicle to enter the intersection or roundabout.

Gap-acceptance models are, however, unrealistic in assuming that drivers are consistent and homogeneous [8, 21]. A consistent driver would be expected to behave in the same way in all similar situations, while in a homogeneous population, all drivers have the same critical gap and are expected to behave uniformly [13] In the real world simulation, driver type may differ and the critical gap for a particular driver should be represented by a stochastic distribution [1].

In gap-acceptance models, estimation of the critical gap has attracted much attention, with use of a mean critical gap [2, 10, 20]. The maximum likelihood estimation of the mean critical gap has been widely accepted [2, 6, 18, 20], but the basic assumption is still that all drivers are consistent.

Investigation of the factors affecting critical gap and follow-up time concludes that drivers use shorter critical gaps at higher flow and delay conditions [17]. Many other factors have also been noted [7, 18, 23]. However, a critical value obtained for any given situation is unlikely to be generally applicable.

Further, at un-signalized intersections or roundabouts in an urban network, adjacent intersections with traffic lights will group the vehicles into a queue (or queues) during the red signal phases, and platoons are thus present (the filtering effect). The filtering of traffic flow by traffic signals has a significant impact on capacity and performance [19]. In particular, the gap-acceptance model can be applied only when no platoon is present [14]. Otherwise, no minor-stream vehicle can enter the intersection or roundabout, as the mean headway within a platoon is supposed to be less than the critical gap. If traffic signal cycles are known and co-ordinated, the platoon pattern may be predictable. If it is not predictable, traditional gap-acceptance models are not readily applicable [14] and does not specifically allow for modeling directional flow [18].

Moreover, gap-acceptance models describe the interaction between the vehicles from minor streams and major streams as *reactive* rather than as *interactive*. In other words, the gap-acceptance models only describe the behavior of entering vehicles and how they react to the gaps in the major streams. According to priority rules, vehicles from major streams have higher priority over vehicles from minor streams. However in reality, *priority sharing* always occurs. Priority sharing is a phenomenon that the major-stream vehicles share priority with minor-stream vehicles. This phenomenon is usually believed to be caused by high volume of traffic flow [22] and saturation on minor streams [7]. It may be generated by the aggressive behavior of driver in a minor stream. It may also be due to courtesy from a driver in one of the major streams. Harwood *et al.* [7] believe it is most often caused by a minor-stream driver compelling a major-stream driver to give way by using a gap so tiny that the latter has to reduce speed. Based on field observations, Troutbeck and Kako [22] indicated that major-stream vehicles could be slightly delayed to accommodate a minor-stream vehicle. Harwood *et al.* [7] described the phenomenon in terms of speed reduction to 85% for a major-stream vehicle.

Traditional gap-acceptance models have failed to take this phenomenon into account, but more recently research in [22] has tried to overcome it by adding an additional factor $C$ to the capacity formula to include the priority sharing effects. This $C$ value ranges from 0 to 1 and depends on headway distribution. Although this modification can improve the accuracy of the capacity formula obtained from previous gap-acceptance models, it has provided little help in analyzing the operation of roundabouts or intersections unless there is evidence or conclusion that priority sharing is directly related to headway distribution.

A number of authors [5, 6, 9] have estimated separate critical gaps for different streams, but the results for intersections and roundabouts are contradictory. Questions of impedance of the vehicles in minor and major streams have also been considered, but findings on the number of opportunities presented for vehicles to move onto the roundabout or intersection are not well substantiated.

Field indications are that position delay should be taken into consideration [24]. Position delay is common on multi-lane minor roads of intersections or multi-lane entrance roads of roundabouts. The diver of a vehicle in the left lane needs extra time to adjust position to avoid sight-blocking caused by the vehicle (and/or people sitting in its front seats) in the right lane of the road.

The MAP method was first proposed by Wang and Ruskin [25], using analogous but more flexible methodology to that of gap-acceptance models (e.g., spatial and temporal details of vehicle interactions can be described using MAP). This facilitates understanding of the interaction among drivers and also can be applied to situations in which headway distributions are insufficient to describe traffic flow.

Based on the MAP method, this paper proposes a Multi-stream Minimum Acceptable Space (MMAS) model by considering the combinations of available space on the multi-lane roundabout. We use three CA-rings to extend previous work on single-lane roundabouts [25] for three-lane roundabouts.

## 3. METHODOLOGY

Vehicles at entrances of multi-lane roundabouts observe the same priority rule as at entrances of single-lane roundabouts. Vehicles on entrance roads of roundabouts moving onto the corresponding lanes of roundabouts need to give way to the vehicles on the roundabouts.

The process for a vehicle to pass a three-lane roundabout can be divided into the following sub-processes.

1. Vehicle arrival at the start of an entrance road (e.g. 100 cells away from the roundabout)
2. Pre-determined destination (before allocation to a lane of the entrance road) and lane allocation (on entrance road)
3. Vehicle movement along an entrance road
4. Position delay: vehicles from an entrance road of roundabouts on the left lane (or middle lane) of an entrance road may be halted for Position Delay Time (PDT) if view impeded by adjacent vehicles. The PDT is the time to adjust position to check opportunity to enter the roundabout)
5. Entry (interaction between vehicles from the entrance and vehicles already on the roundabout)
6. Navigation of the roundabout
7. Vehicles exit from the roundabout

In this paper, we focus on the fifth and seventh processes identified above, as the others are similar to that for the single-lane roundabouts described in [24, 25].

Note that it is more realistic to assume that for all vehicles the destinations are predetermined and remain unchanged throughout the roundabout maneuver.

The lane allocation process for a three-lane roundabout is relatively simple as left-turning vehicles use the outer lane of the roundabout, straight-through vehicles will use the middle lane of the roundabout, and the right–turning vehicles use the inner lane of the roundabout. However, the interaction at the entrance of a three-lane roundabout is more complicated than for a single-lane roundabout.

### 3.1 Interaction at Roundabout Entrances

We use three CA-rings (three cellular automata rings with the same centre but different diameters) to simulate three-lane roundabouts. All rings have the same number of cells and vehicles can move ahead one cell in each time step when they navigate the roundabout. In other words, we assume that the vehicles in all lanes traverse the same number of radians in the same period of time. This assumption is permitted by the fact that the speeds of a vehicle driving in different rings (with different radius) are different. The shorter the radius, the lower speed that vehicle can move.

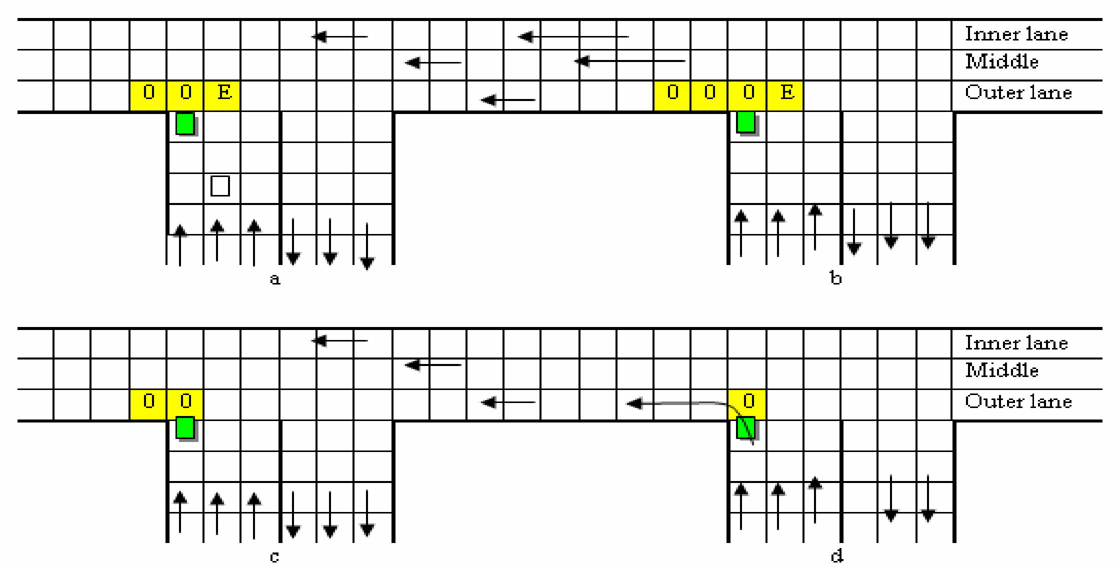

Fig. 1. Vehicle in the left lane of the entrance road with (a) rational, (b) conservative, (c) urgent and (d) radical driver behavior

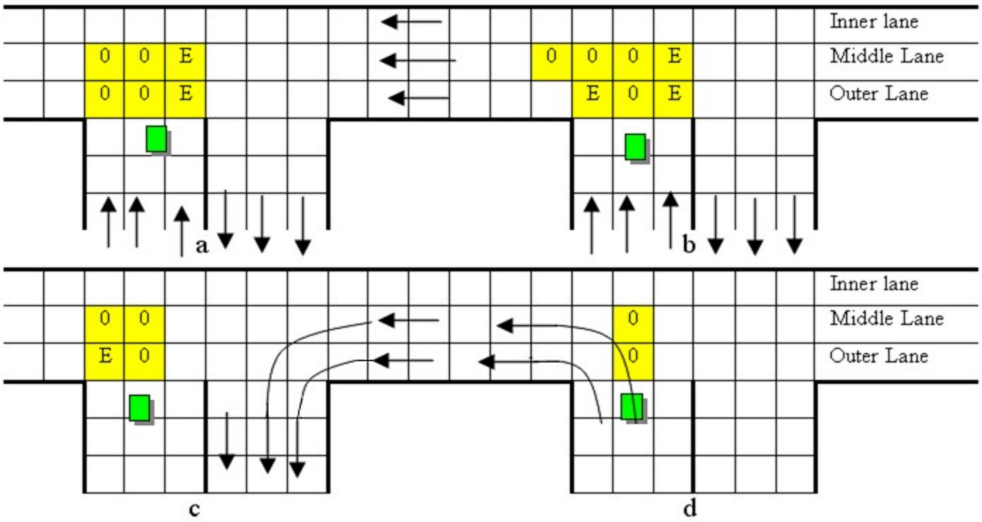

Fig. 2. Vehicle in the middle lane of the entrance road with (a) rational, (b) conservative, (c) urgent and (d) radical driver behavior

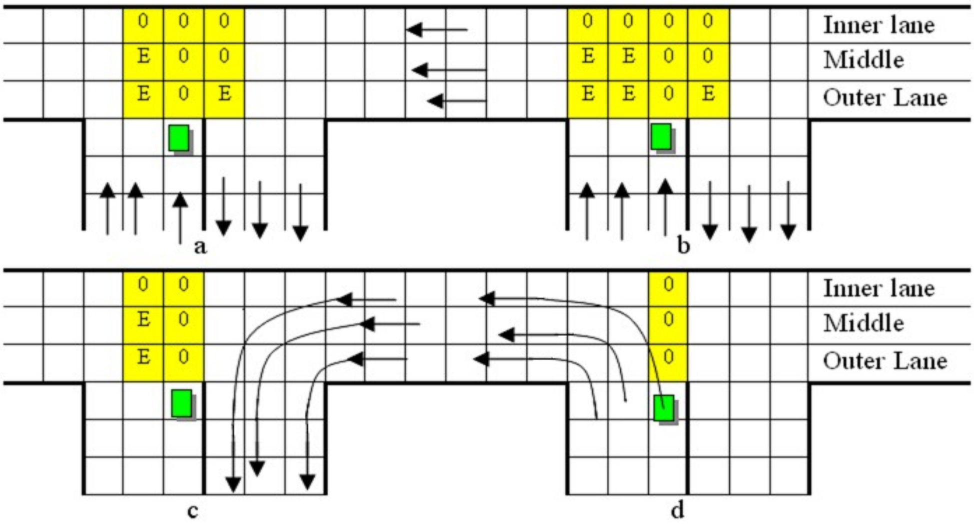

Fig. 3. Vehicle in the right lane of the entrance road with (a) rational , (b) conservative, (c) urgent and (d) radical driver behavior

In this paper, we use vehicles on the left, middle and right lanes of the entrances of three-lane roundabouts to show the interaction among drivers. In order to simplify the representation, the shape of the arc of a roundabout with an entrance road can be changed to resemble Fig. 1-3, which look like T-intersections. The paths of vehicles in the entrance road are shown in Fig. 1(d), 2(d) and 3(b), while the paths of vehicles exiting from the roundabout are shown in Fig. 3(c). When a vehicle on the middle or right lane of the entrance road needs to change lane from the outer lane to the middle and/or inner lane on the roundabout, it crosses two cells diagonally. Likewise, this is true for the vehicles coming from the inner lane (and/or the middle lane) to the outer lane (see the curved arrows). In other words, when the vehicle changes lane on the roundabout, it moves ahead for one cell at the same time.

Following the MAP method, we use similar figures to explain our MMAS model and the conditions required by vehicles from entrance roads. Driver behavior is categorized into four groups: conservative, rational, urgent and radical, with associated probabilities [25].

For a three-lane roundabout, the required conditions for the target vehicle (shaded) in the left lane of the entrance road in this time step are indicated by the spaces required (shaded cells) in Fig. 1(a)-(d), based on four different driver behaviors. Fig. 2 and 3 show entering vehicles from the middle and right lane of the entrance road of a three-lane roundabout.

The requirement for each cell is indicated by “0” or “E”, where “0” means that the cell must be vacant and “E” means that the cell is either vacant or occupied by a non-circulating vehicle. A non-circulating vehicle is one either just entering the roundabout from an entrance road or about to leave the roundabout in the next time step. All space requirements are indicated cell by cell (with the same notation, either “0” or “E”).

Theoretically, the left lanes of entrance roads and the outer lanes of roundabouts are designed for left-turning vehicles only. Thus, left-turning vehicles do not need to check conditions before entering the roundabout. However, in practice, checking is necessary for left-turning vehicles. Therefore, we build this checking into the models.

For vehicles entering from the middle and right lanes, we assume that drivers use similar space requirements for each lane that the vehicles will traverse. Thus, the MAAS covers 3 cells in both outer and middle lanes of the roundabout in Fig. 2(a), while the MAAS covers 3 cells in each of the three lanes of the roundabout in Fig. 3 (a).

The assumption of a similar space requirement for each lane is justified by the argument that drivers’ heterogeneous behavior is partially determined by their types and individual characteristics, such as sex, age and driving experience, etc. [16], and not by their location in different lanes. Some investigations indicate age to be an important factor in determining not only driver reaction time but also driver behavior [12, 16]. Another argument is that a driver who accepts a small gap in one lane is more likely to use a larger gap in the other lane in order to compensate for the risk [26].

Further suggestions are that two types of interactions are involved, crossing and merging, or that the passing speeds which the entering vehicle may reach to pass the near and far lane are different. Larger gaps in the near lane and smaller gaps in the far lane are reported, together with other suggestions for why drivers are very different [6], but these results are contradicted by the results in [5, 9].

Our view is that all possibilities reflect an individual driver. A “risk-taker” takes the same amount of risk either way, no matter whether the risk is equally or unequally distributed between the two lanes (in agreement with [5]). On the other hand, a “risk-averse” decision implies equal caution in both lanes. The assumption of equal space requirements in each lane can be seen as a compromise in this case.

### 3.2 Interaction on Roundabouts

Immediately after entering a roundabout, the vehicles from the middle and right lane of the entrance roads move from the outer lane into the middle and inner lane respectively. They are assumed to move along the middle lane and inner lanes until they arrive at their destinations (exit roads). In other words, they do not change lanes except on entering and exiting. This assumption is supported by the fact that unnecessary lane-changing on roundabouts is not common [24].

For a three-lane roundabout, the exit of vehicles in outer and middle lanes of roundabouts is expected to be free flow according to the give-way rules in New Zealand. However, the exit of vehicles on the inner lane may be blocked by the vehicles driving on the middle lane. Thus, we use a probability, Give-Way Rate (GWR), to simulate this random result of driver interaction. The probability can be in a range from 0 (no driver gives way) to 1 (all drivers give way).

## 4. MODEL EXPERIMENTS

In order to study roundabout performance, the following experiments were carried out: (i) throughput vs. arrival rate, (ii) throughput vs. turning rates, (iii) PDT and GWR on the roundabout vs. throughput, (iv) driver behavior vs. throughput, (v) queue formation on the roundabout and individual roads and (vi) individual road performance, e.g., queue lengths, etc. Only results from (i), (ii) and (iv) are presented in this paper. In each experiment, the length of each entrance road is *100* cells. If the throughput is printed in bold, as in Table 1, it means that the queue length has reached the length of the road on one or all entrance roads, i.e. saturated. All experiments were carried out for *3* x *36,000* (= *3* x *60* x *60* x *10* = *3* x *10* hours) time-steps. Arrival rate (AR) = *0.01* is equivalent to *AR* = *36*vph (vehicles per hour).

### 4.1 Relationship between Throughput and Arrival Rates

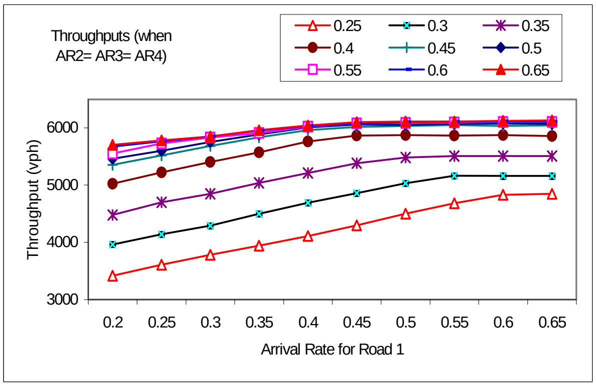

Fig. 4. Throughputs vs. arrival rates.

For single-lane roundabouts, the throughput and arrival rates are closely related as all arriving vehicles need to wait for a Minimum Acceptance sPace (MAP) to enter the roundabout [25]. However, for three-lane roundabouts, the throughput also depends on the turning rates. In particular, it depends on the left turning rates as the left-turning traffic on the left and outer lanes is theoretically free flow. The larger proportion of left-turning vehicles the higher the throughput. Thus, we can only find out the relationship between throughput and straight-through and right-turning vehicles. Therefore, in the following experiments, the left-turning vehicle portion is assumed to be fixed at *0.25*. In other words, only *25%* of arriving vehicles will turn left.

Fig. 4 shows the throughput and arrival rates of three-lane roundabout. The arrival rates of three roads ($AR_2$, $AR_3$ and $AR_4$) are taken to be the same and allowed to range from *0.25* to *0.65*. The arrival rate of road 1 ($AR_1$) also increases from *0.20* to *0.65*. The findings can also be summarized in the following two expressions. When the arrival rate of the entrance road ≥ Critical Arrival Rate (CAR), saturation occurs on the entrance road.

The empirical relationships between $CAR_1$ (of road 1) and the arrival rates of the other three roads are:

1. If $AR_i < 0.45$, then $CAR_1 = 0.8 - AR_i$ (1)
2. If $AR_i \geq 0.45$, then $CAR_1 = 0.35$ (2)

where *i (subscript)* = *2*, *3* or *4*.

The throughput of the three-lane roundabout continues to increase with arrival rate when the middle and inner lanes of the roundabout are saturated (i.e. arrival rate > CAR). The situation is different from that in single-lane roundabouts [25]. Since left-turning vehicles use the left lane of an entrance road, traffic on the left lane is always free flow. Therefore, when arrival rates increase, the number of left-turning vehicles continues to increase. Consequently throughput also increases.

As for single-lane roundabouts [25], balanced arrival rates ($AR_1=AR_2=AR_3=AR_4$) are found to lead to improvement in the operational performance of the roundabout. If we define the *effective throughput* as the throughput when no entrance road is saturated, the maximum effective throughput that we find is *5806* vph when $AR_1=AR_2=AR_3=AR_4=0.43$. When arrival rates are not equal, the effective throughput is less than the optimal one.

## 4.2 Relationship between Throughput and Turning Rates

Fig. 5 shows the relationship between throughput and right-turning rates (RTR). When $AR_1=AR_2=AR_3=AR_4<0.3$, traffic flows freely and turning rates have no impact on throughput. When $AR_1=AR_2=AR_3=AR_4=0.3$ and the right-turning rate is *0.35*, traffic still flows freely. However, when right-turning rates are equal to *0.45*, entrance roads are saturated and turning rates do have an effect on throughput. When $AR_1=AR_2=AR_3=AR_4>0.3$, the turning rate also has an effect on throughput: In creasing right-turning rate (RTR) by *0.10* this gives around a *10%* decrease in the throughput when the entrance roads are saturated. The relationship between the RTR and its CAR can be roughly expressed by the following empirical relation:

$$CAR = 0.4 - 0.5(RTR - 0.35) \quad (3)$$

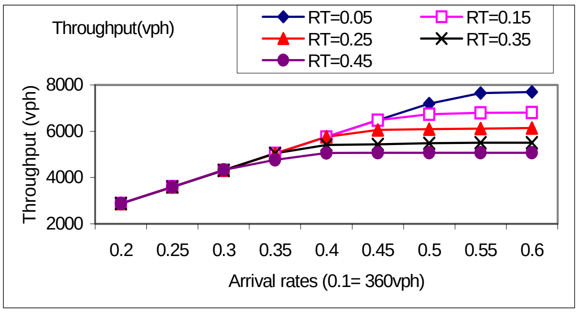

Fig. 5. Throughputs change vs. right-turning rate.

## 4.3 Driver Behavior

The impact of driver behavior on throughput can be shown by the following experiments. We assume that the sum of probabilities of conservative ($P_{co}$), rational ($P_{ra}$), urgent ($P_{ur}$) and radical ($P_{rad}$) behavior is equal to 1 [25]. In other words, for simplicity, all drivers are of one type in the first instance. These are clearly special situations, which are examined to give us some indication of how extremes of driver behavior impact on three-lane roundabout performance. A mixed driver set is also possible of course and is easily tested with our models.

| Driver Behavior | Arrival Rates ($AR_1= AR_2=AR_3=AR_4$ ) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.30 | 0.35 | 0.40 | 0.45 | 0.50 | 0.55 | 0.60 |
| *Pco =1* | 4322 | **4475** | **4512** | **4552** | **4582** | **4589** | **4620** |
| *Pra=1* | 4320 | 5038 | 5764 | **6012** | **6053** | **6094** | **6112** |
| *Pur=1* | 4319 | 5061 | 5768 | **6345** | **6398** | **6434** | **6494** |
| *Prad=1* | **83** | **95** | **62** | **19** | **26** | **19** | **33** |

Table 1. Driver behavior vs. throughput

Table 1 shows the results for a three-lane roundabout. The arrival rates are equal in each column. For all $AR= (AR_1=AR_2=AR_3=AR_4=)\ 0.30$ in column 1, all throughputs are the same except that of $P_{rad} =1$. When $P_{co} =1$ and all $AR \geq 0.35$, throughput reaches a maximum and a saturated situation occurs on entrance roads, while traffic flow on the roundabout remains in free flow at all times. When $P_{ra}=1$ or $P_{ur} =1$, throughputs are different, and higher than those for $P_{co} =1$. Traffic flow on the roundabout again remains free at all times. When $P_{rad} =1$ and all $AR >0.30$, throughputs are reduced compared to the others discussed, as congestion forms on the roundabout. Similar results are also found with other turning rates.

Thus, as for single-lane roundabouts [25], collective conservative behavior decreases throughput. In contrast, collective radical behavior can cause congestion on the roundabout and decreased throughput, compared to rational behavior. A distribution of driver behavior is more realistic of course, but our results do reproduce the phenomenon of congestion on a three-lane roundabout due to too many drivers not observing the give-way rules.

## 5. CONCLUSIONS

In this paper, we proposed Multi-stream Minimum Acceptable Space (MMAS) Cellular Automata (CA) models to simulate driver behavior and its effects on traffic flow at three-lane roundabouts. Position Delay Time (PDT) and Give Way Rate (GWR) are also proposed to reflect the real world situations of roundabout operations.

It is expected that throughput will linearly increase with arrival rates when no entrance road is in a saturated situation. Throughput reaches a maximum when the arrival rate reaches a critical value on one or more roads. When the arrival rate is higher than the critical value, saturation occurs on one or more roads. The operational performance of the roundabout is improved when arrival rates are balanced ($AR_1=AR_2=AR_3=AR_4$). Throughput decreases as right-turning rates increase when one or more roads are saturated, as vehicles, on average, need to travel longer distances on the roundabout.

For three-lane roundabouts, theoretically, left-turning vehicles flow freely. The major impacts of driver behavior are on the middle and inner lanes of roundabouts. From our experiments, we can conclude that collective radical behavior or lower GWR can cause gridlock on the roundabouts. There is some difference between rational and urgent behavior in respect of throughputs. Conservative behavior leads to decreased throughput.

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