# Modeling Origin-Destination Effects on Roundabout Operations and Inflow Control

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**Abstract:** Traffic flows around roundabouts have been found to be dependent on origin-destination flows, but the true nature of this relationship is not properly understood. Present analyses are based on either gap acceptance models or empirical models. These models do not properly account for the impact of origin-destination flows on roundabout operations. This has limited the possibility to develop strategies that improve roundabout operations by controlling inflows. This research proposes a theory to analyze roundabout traffic flows and a strategy to determine inflows into a roundabout that would maximize the outflow from the roundabout. This strategy could be implemented through use of signals to meter vehicles at the entry. To achieve this, a theoretical framework is proposed based on the macroscopic fundamental diagram for urban networks. The theory and strategy is then tested using microscopic simulation. It was found that the outflow from a roundabout is dependent on the average flow and the average trip length around the roundabout. The average trip length is a function of the origin-destination flows. **DOI: 10.1061/(ASCE)TE.1943-5436.0000394.** *© 2012 American Society of Civil Engineers.*

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## Introduction

Gridlocks have been observed at roundabouts during periods of high demand. More specifically, the entry capacities of approaches to a roundabout have been found to decrease with increasing number of circulating vehicles. Even though circulating flows around a roundabout have been found to have a significant impact on the operations of the roundabout, there is no clear theoretical foundation that explains the effects of origin-destination flows on circulating flows and roundabout operations. This has limited the development of a systematic method to determine efficient inflows into a roundabout.

Though several models are being used to estimate capacity, almost all of them can be grouped under two distinct families: the empirical approach and the theoretical gap acceptance approach. The regression models developed by the Transportation Research Laboratory (TRL) in the United Kingdom (Brown 1995) are empirical models, while the models used in the Highway Capacity Manual (HCM) (Transportation Research Board 2000), aaSIDRA and AUSTROADS, have been termed as theoretical gap acceptance models.

Empirical models were developed using regression analysis on observed volumes at roundabouts. Though these models have been useful in understanding factors that affect capacity, and could be applied to roundabouts that are similar to the sample roundabouts used for the regression analysis, they cannot be generalized. Akcelik (2003) also found that the empirical-based TRL models underestimated capacity during low circulating flows and overestimated capacity during high circulating flows.

The theoretical gap acceptance models provide an analytical framework and, compared with empirical models, are more generalizable. Most of the theoretical gap acceptance models, such as the HCM (Transportation Research Board 2000), model roundabouts as independent *T* intersections with gaps appearing in the circulating stream. Similar analysis of roundabouts as independent *T* intersections have been conducted by Akcelik (1994) using aaSIDRA, and more recently by Chevallier and Leclercq (2007) using a macroscopic dynamic model using fictive lights. One of the major drawbacks of modeling roundabouts as independent *T* intersections is its failure to recognize the effects of origin-destination flows on capacity. Studies (Chung et al. 1992; Chung 1993) have found that imbalanced flows and origin-destination paths have a significant impact on roundabout capacities. Recent field studies (Chen and Lee 2011) found that unbalanced entrance flow patterns can intensify the queue and delay for the overall roundabout. Akcelik (2005) observed that the present HCM (Transportation Research Board 2000) model as well as the TRL (Brown 1995) models fail to consider the effect of the origin-destination paths, and these models tend to over predict capacities under conditions of unbalanced flows.

To correct the capacity calculations for unbalanced flows, an origin-destination factor was introduced in the aaSIDRA modeling framework (Akcelik 2004). The origin-destination factor was used to reduce capacity during high circulating volumes, but its incorporation lacked a theoretical framework and was based on empirical analysis. Despite the use of the origin-destination factor, Krogscheepers and Roebuck (2006) found discrepancies in this capacity analysis. They found that the origin of the circulating vehicle also had a significant effect on the capacity. The need to explain the impact of circulating vehicles and unbalanced flows on capacity requires a new parsimonious framework that can accurately model these characteristics.

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Both families of models have been unable to provide a systematic theory for the effects of origin-destination flows on roundabout operations. These effects are usually incorporated into the existing theory by using adjustment factors, which are nongeneralizable and lack a theoretical foundation.

Based on recent advances (Daganzo 2007; Geroliminis and Daganzo 2007) made in the area of macroscopic fundamental diagram (MFD) for urban networks, this research demonstrates the existence of the MFD for the average circulating flow at roundabouts. Further, it is shown that this MFD is independent of the origin-destination flows. In fact, the average trip length based on the origin-destination flows is shown to affect the outflow. These properties are used to propose a measure of "capacity" of a roundabout.

The objective of this research is to develop a control strategy for inflow into the roundabout to ensure efficient circulating flows. To develop such a strategy, it is critical to develop a theory that can explain the impact of origin-destination flows on the roundabout operations.

The next section presents a modeling framework that incorporates the effects of origin-destination flows on roundabout operations. In the section titled "Simulation Results," the theory is tested using microscopic simulation. Based on the theory, an inflow control strategy is formulated and tested, and the final section presents the conclusion of this research.

## Modeling Framework

Measurements and relationships between macroscopic traffic variables—flow, concentration, and speed—have been extensively studied for traffic streams both in theory and in the field (Edie 1965; Gazis 1974). On a network level, the relationships between these macroscopic variables have also been studied in simulation experiments (Mahmassani et al. 1984; Williams et al. 1987; Geroliminis and Daganzo 2007) and through field studies (Ardekani 1984; Geroliminis and Daganzo 2008). This research utilizes similar concepts to derive relationships between average circulating flow and concentration, as well as, the outflow and the average trip length at a roundabout.

### Macroscopic Fundamental Diagram

Traffic flow variables are defined over section $ij$ around a roundabout. Section $ij$ is the part of the roadway between entry zone $i$ and the nearest exit zone $j$ (Fig. 1). Section $ii$ is the section between exit zone $i$ and entry zone $i$.

The average flow ($\bar{Q}$) around a roundabout is defined as the weighted average of flow ($Q_{ij}$) in section $ij$, weighted by the length ($l_{ij}$) of section $ij$, which includes sections $ii$:

$$\bar{Q} = \frac{\sum_{(i,j)} l_{ij} Q_{ij}}{\sum_{(i,j)} l_{ij}} \tag{1}$$

The average velocity ($v_{ij}$) on a roundabout section $ij$ is defined as the sum of velocities of all vehicles in section $ij$ divided by the number of vehicles ($n_{ij}$) in section $ij$:

$$v_{ij} = \frac{\sum_{m\in(ij)} v_m}{n_{ij}} \tag{2}$$

On section $ij$ around a roundabout, the fundamental speed/flow/density relationship will hold:

$$Q_{ij} = k_{ij} v_{ij} \tag{3}$$

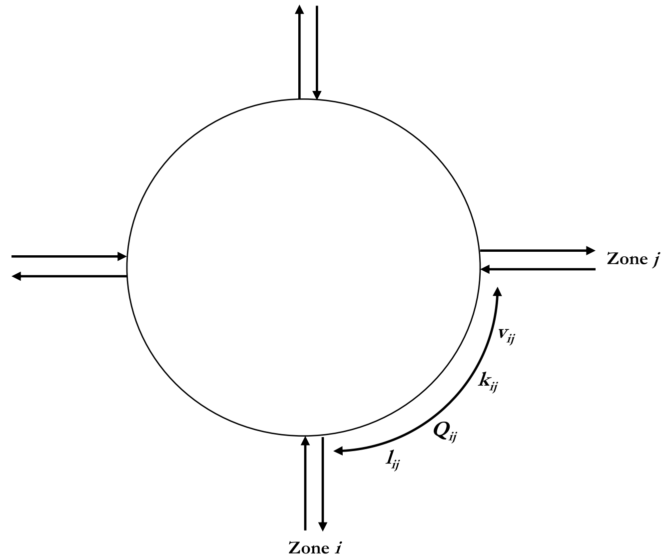


**Fig. 1.** Dependence of average flow around the roundabout to number of circulating vehicles

Multiplying Eq. (3) by the length of section $ij$ ($l_{ij}$) and summing both sides over all sections $ij$ and dividing by the total length of the roundabout results in the following equation:

$$\frac{\sum l_{ij} Q_{ij}}{\sum l_{ij}} = \frac{\sum l_{ij} k_{ij} v_{ij}}{\sum l_{ij}} \tag{4}$$

The left side of Eq. (4) is defined as the average flow around a roundabout ($\bar{Q}$), where $l_{ij}k_{ij}$ = the number of vehicles in adjacent section $ij$ ($n_{ij}$):

$$\begin{aligned}\bar{Q} &= \frac{\sum (l_{ij}k_{ij}) v_{ij}}{\sum l_{ij}} = \frac{\sum (n_{ij}) v_{ij}}{\sum l_{ij}} = \left(\frac{\sum n_{ij}}{\sum l_{ij}}\right)\left(\frac{\sum (n_{ij} v_{ij})}{\sum n_{ij}}\right) \\ &= K\left(\frac{\sum \sum_{m\in(ij)} v_m}{\sum n_{ij}}\right)\end{aligned} \tag{5}$$

where $K$ = the average density in the roundabout that is measured as the total number of vehicles divided by the total lane length on the roundabout. In Eq. (5), the sum of velocities of all vehicles [$\sum \sum_{m\in(ij)} v_m$] on the roundabout is divided by the total number of vehicles ($\sum n_{ij}$); this by definition is the average velocity of the circulating vehicles ($\bar{V}$):

$$\Rightarrow \bar{Q} = K\bar{V} \tag{6}$$

Under congested conditions, the density around the roundabout can be assumed to be homogenous, and if $f(k)$ describes a monotonically decreasing function between the speed and density on an individual section, Eq. (6) can be rewritten as

$$\bar{Q} = Kf(K) \tag{7}$$

Because on road section $ij$ the flow-density relationship [$k_{ij}\, f(k_{ij})$] is unimodal and concave, Eq. (7) will be unimodal and concave. Therefore, the relationship between flow and density around a roundabout will have the shape of the macroscopic fundamental diagram.



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## *Relationship between Outflow and Average Circulating Flow*

The derivation of the relationship between the average circulating flow and outflow around a roundabout is exactly the same as that shown for urban networks by Geroliminis and Daganzo (2007).

The outflow ($O$) from the roundabout is the number of vehicles finishing their trips around the roundabout per unit time, while the total distance traveled by vehicles around a roundabout per unit time is termed production ($P$). The average travel time for a vehicle circulating around a roundabout is represented by $\bar{\tau}$, the average speed is represented by $\bar{V}$, and $\lambda$ is the total inflow into the roundabout from all approaches. Under the assumption of steady state conditions, the outflow should be equal to the inflow during a small time interval, where the inflow and outflow do not change:

$$P = n.\bar{v} \tag{8}$$

$$\frac{O}{P} = \frac{O}{n\,\overline{V}} = \frac{O}{\lambda\,\bar{\tau}\,\overline{V}} \tag{9}$$

During steady state conditions, $O = \lambda$. In addition, $\bar{\tau}\overline{V}$ is the average trip length $\bar{L}$:

$$\frac{O}{P} = \frac{1}{\bar{L}} \tag{10}$$

Based on the definition of production and Eq. (1):

$$P = \sum Q_{ij} l_{ij} = \frac{\sum Q_{ij} l_{ij}}{\sum l_{ij}} \sum l_{ij} = \bar{Q} l \tag{11}$$

Therefore, Eq. (10) can be rewritten as

$$\Rightarrow O = \frac{\bar{Q} l}{\bar{L}} \tag{12}$$

Eq. (12) would result in a linear relationship between outflow and average circulating flow, provided that the average trip length is constant. This is not trivially true, because as the circulating flow increases, it constrains the inflow. Constrained inflow into the roundabout could affect the average trip length. Fortunately, invoking the theory of constant merge ratio, it can be shown that the average trip length remains constant in congested conditions.

The average trip length of a vehicle is determined by the number of vehicles that enter the roundabout, and their destinations. The variable $f_{ij}$ is the lane length from entry at origin $i$ to exit at destination $j$. The variable $p_{ij}$ is the fraction of vehicles traveling from origin $i$ to destination $j$ at a roundabout. Variable $Q_i$ is the inflow rate from an entry approach $i$. Therefore, the average trip length can be written as

$$\bar{L} = \frac{\sum_i Q_i T \sum_j p_{ij} f_{ij}}{\sum_i Q_i T} \tag{13}$$

Earlier studies show that the ratio of merging traffic flows is constant (Papageorgiou et al. 1990; Daganzo 1995; Daganzo 1996; Ni and Leonard 2005). In fact, the merge ratios can be estimated with reasonable accuracy by the lane ratios (Cassidy and Ahn 2005; Bar-Gera and Ahn 2010). At a roundabout, the inflows merge into the traffic circulating around a roundabout; this circulating flow is represented by $Q_c$. Therefore, Eq. (13) can be rewritten as

$$\bar{L} = \frac{\sum_i \frac{Q_i}{Q_c} T \sum_j p_{ij} f_{ij}}{\sum_i \frac{Q_i}{Q_c} T} = \frac{\sum_i \sum_j \lambda_i p_{ij} f_{ij}}{\sum_i \lambda_i} \tag{14}$$

where $\lambda_i = Q_i / Q_c$.

Because the merge ratios are constant at each of the merge points on the roundabout, it can be concluded that the average trip length of vehicles flowing around a roundabout is constant for a given origin-destination flow. Therefore, the coefficient $l/\bar{L}$ in Eq. (12) is constant. Hence, the relationship between outflow and average flow is linear. Though this conclusion is similar to the conclusions made by Geroliminis and Daganzo (2007), the extension from urban networks to roundabouts requires invoking the concept of constant merge ratio.

For a traffic engineer, the key parameters to measure are the lane lengths between the approach and exits (which can be easily determined from the geometry of the roundabout), average flow around the roundabout, and average trip length.

The average flow around a roundabout, evaluated using Eq. (1), requires flows between each approach and exit segment, and can be determined using counters. The lane lengths between the approach and exits can be determined by studying the geometry of the roundabout.

The calculation of average trip length as shown in Eq. (14) requires the turning movements ($p_{ij}$), which can be collected using video or field-observed data; the lane length ($f_{ij}$), which can be determined by the geometry; and finally the merge ratio, which can be determined as the ratio of number of lanes (Cassidy and Ahn 2005; Bar-Gera and Ahn 2010).

## Simulation Results

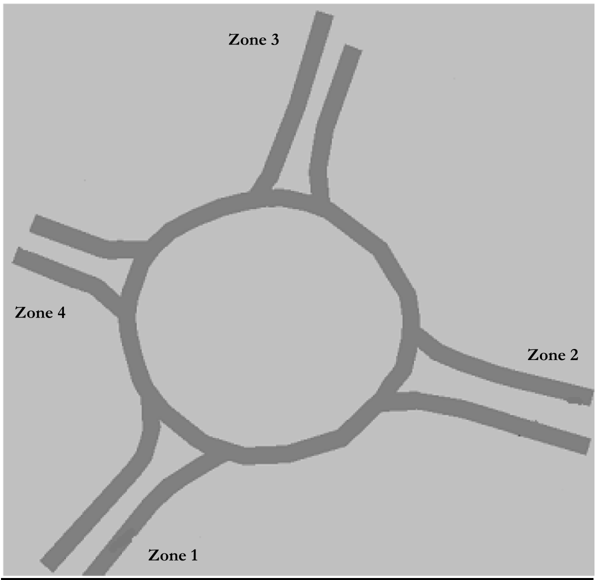
The relationships between average flow, outflow, and density developed in the previous section were tested using microscopic simulation. Bared and Edara (2005) compared the performance of VISSIM (2007), RODEL, and aaSIDRA with two high-capacity modeled roundabouts and their integration into smart signalized streams. Based on comparisons of the results with real data collected from various sites in the United States, VISSIM (2007) outputs were found to be closer to real data. Therefore, the relationships discussed in the earlier section were studied for different roundabouts using VISSIM (2007) microsimulation.

### *One-Lane Roundabout*

The relationships derived in the previous section were tested on a single-lane roundabout with a diameter of 180 ft. Data regarding speed, flow, and density were collected for each section of the roundabout averaged over 60 s from the simulation. As discussed in the paragraph prior to Eq. (8), the data collection intervals should be in steady state such that the outflow is equal to inflow. Considering this, the 60-s time interval was considered to be sufficient. The results were obtained through five simulation runs, with each run representing a period of 1 h. The configuration of the one-lane roundabout and the demands from each origin to destination are shown in Fig. 2.

The relationship between the outflow from the roundabout and the average circulating flow was found to be consistent with the theoretical model developed. This is shown in Fig. 3. A regression analysis further supports the theory describing the linear relationship between the outflow and average circulating flow. This also confirms that the ratio of average trip length and the total lane length of the roundabout is a constant value for given origin-destination flows, and is equal to 2.96.

The relationship between the average circulating flows versus density is shown in Fig. 4, and has the shape of an MFD. The maximum value of the MFD can be thought of as the capacity of the roundabout.




| Origin \ Destination | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| Zone 1 | 0 | 250 | 350 | 650 |
| Zone 2 | 400 | 0 | 600 | 600 |
| Zone 3 | 500 | 300 | 0 | 200 |
| Zone 4 | 600 | 300 | 600 | 0 |

**Fig. 2.** One-lane roundabout in VISSIM (2007) with demand from each approach

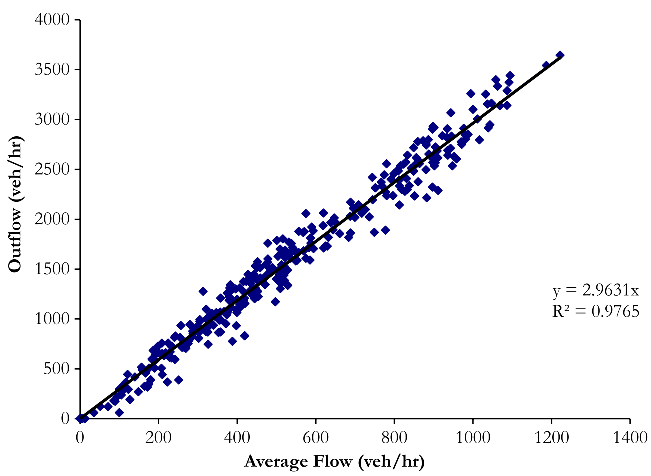



**Fig. 3.** A regression fit between outflow and average circulating flow for a one-lane roundabout

Due to the linear relationship between the outflow and average circulating flow, the dependence of outflow on density would be expected to be similar to the relationship between average circulating flow and density, and is shown in Fig. 5.

## *Two-Lane Roundabout*

To test the robustness of the theory, the models were tested for a two-lane roundabout. The configuration and origin-destination specifications are shown in Fig. 6. The exits and approaches to the roundabout also had two lanes. The radius of the roundabout was 180 ft. The data were collected using exactly the same method described for a single-lane roundabout.

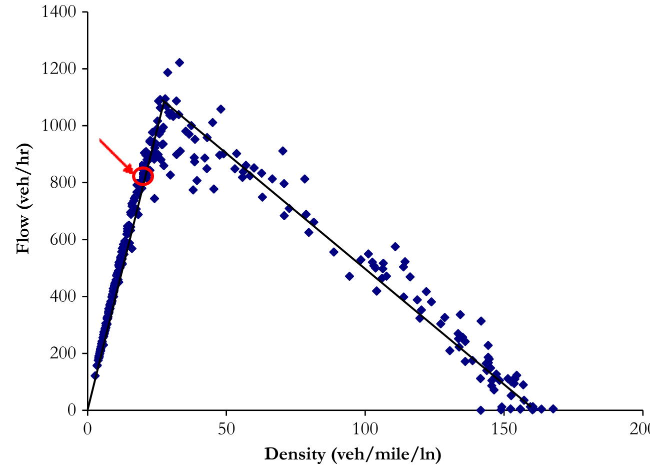



**Fig. 4.** Relationship between average circulating flow and density around a one-lane roundabout

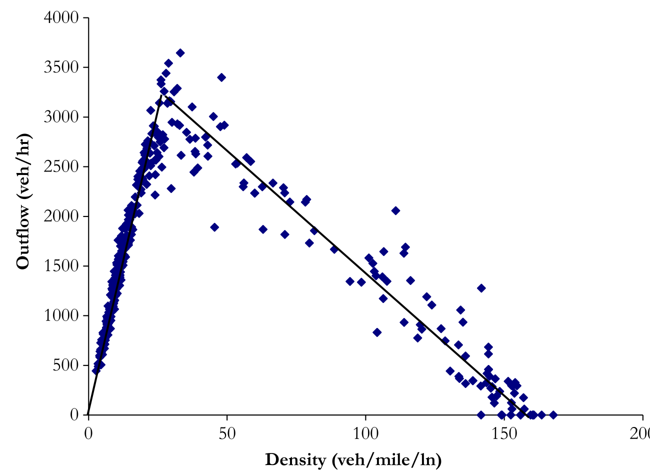



**Fig. 5.** Relationship between outflow and density around a one-lane roundabout

Vehicles were loaded in a manner that was similar to the loading of the one-lane roundabout. The relationship between outflow and average circulating flow is shown in Fig. 7, while the relationship between average circulating flow and density and between outflow and density are shown in Figs. 8 and 9, respectively.

Once again, the relationship between the outflow from the roundabout and the average circulating flow was found to be consistent with the theoretical model developed. A regression analysis, shown in Fig. 7, further supports the theory for two-lane roundabouts, and confirms that the ratio of average trip length and the total lane length of the roundabout is a constant value for given origin-destination flows, and is equal to 3.15.

Fig. 8 shows the relationship between the average circulating flow and density. The trends were found to be similar to that observed in the simulation study for one-lane roundabouts. The relationship between average circulating flow for a two-lane roundabout and density was not found to change for different average trip lengths, indicating the relationship between average circulating



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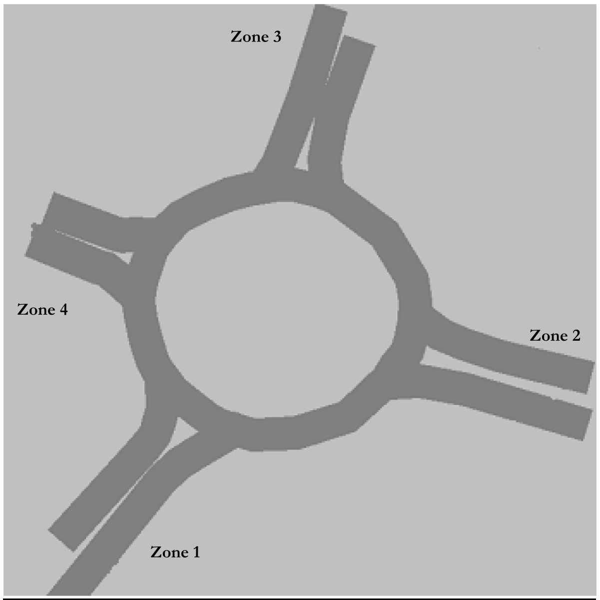


| Destination / Origin | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| Zone 1 | 0 | 200 | 800 | 600 |
| Zone 2 | 800 | 0 | 400 | 800 |
| Zone 3 | 200 | 600 | 0 | 800 |
| Zone 4 | 100 | 200 | 500 | 0 |

**Fig. 6.** Two-lane roundabout in VISSIM (2007) with demand from each approach

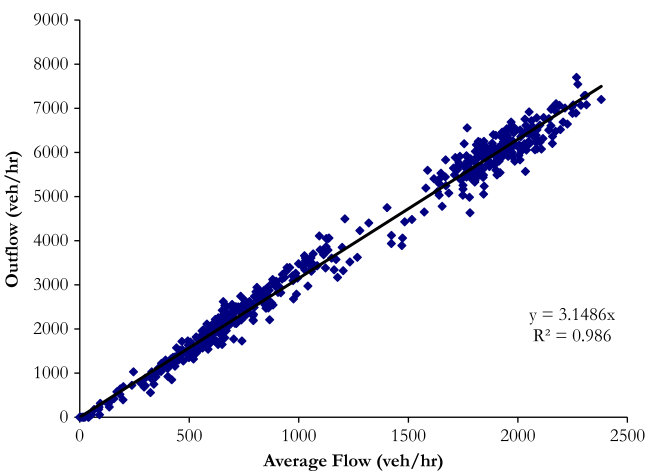


**Fig. 7.** A regression fit between outflow and average circulating flow for a two-lane roundabout

flow and density is a property of the configuration of the roundabout and independent of origin-destination flows.

At first, the average circulating flow increases until a critical density and then suddenly decreases. Due to the linear relationship between outflow and average circulating flow, a similar trend was observed for the relationship between outflow and density (Fig. 9) and average circulating flow and density (Fig. 8). Again, the trends of the graphs were found to be similar to a one-lane roundabout.

As expected, the two-lane roundabout was found to have a larger maximum average circulating flow as compared with

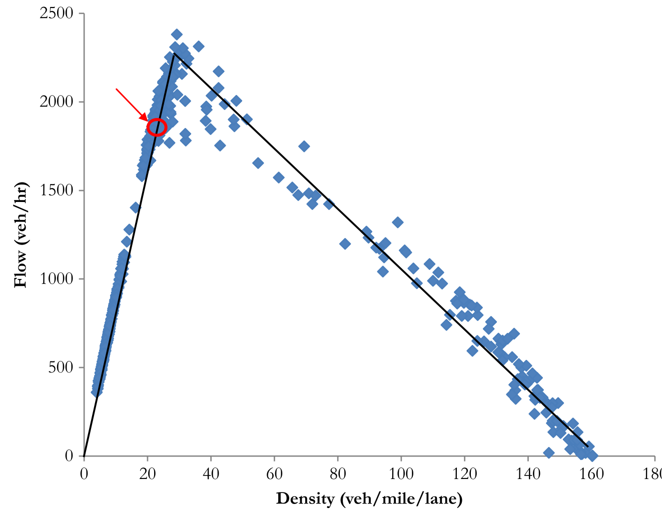


**Fig. 8.** Relationship between average circulating flow and density around a two-lane roundabout

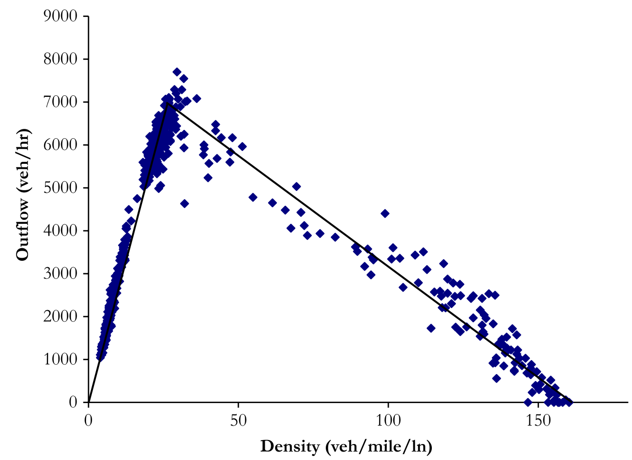


**Fig. 9.** Relationship between outflow and density around a two-lane roundabout

a single-lane roundabout. This indicates that as the number of lanes increases, the maximum average circulating flow increases. Roundabout configurations should be selected in a manner that would increase the maximum average circulating flow.

## Control Strategy

The theoretical framework developed in the previous sections is used to propose a method to determine efficient inflows around a roundabout. This is then tested on both single-lane and two-lane roundabouts, using a VISSIM (2007) microsimulator.

The number of vehicles $n$ circulating in a roundabout can be described by

$$\frac{dn}{dt} = Q_{in} - Q_{\text{out}} \tag{15}$$

where $Q_{in}$ = the sum of flows from all entry approaches and $Q_{\text{out}}$ = is the outflow ($O$) derived in Eq. (12). So far, the average circulating flow has been described as a function of density, but

because the average density is the ratio of total vehicles circulating and the length of the roundabout, the average circulating flow is essentially a function of the number of vehicles circulating $[\bar{Q}(n)]$. Therefore

$$\frac{dn}{dt} = \sum_{j \in \text{Approaches}} Q_j - \frac{l\,\bar{Q}(n)}{\bar{L}} \tag{16}$$

In a study of urban gridlock, Daganzo (2007) used a formulation similar to that described previously to develop an *A-B* strategy to improve the efficiency of the network. The *A-B* strategy stated that the inflow should be maintained at the maximum outflow. Applying the same concept to roundabouts, it can be observed from Eq. (16) that if the inflow is greater than the outflow, then the number of vehicles in the network increases to the point of gridlock. To ensure optimal operations, the total inflow should be maintained at the maximum outflow ($Q_{\text{out}}^{\text{max}}$). Maximum outflow occurs when the average circulating flow around the roundabout is the largest. Because the maximum average circulating flow ($\bar{Q}_{\text{max}}$) was only affected by the configuration of the roundabout, this quantity can be used to describe the capacity of the roundabout.

To ensure that there is no gridlock, the total inflow should be less than or equal to the outflow:

$$\sum_{j \in \text{Approaches}} Q_j \le Q_{\text{out}}^{\text{max}} \tag{17}$$

Based on Eq. (12):

$$Q_{out}^{\text{max}} = \frac{l\bar{Q}_{\text{max}}}{\bar{L}} \tag{18}$$

For optimal operations, the total inflow should be equal to the maximum outflow:

$$\sum_{j \in \text{Approaches}} Q_j = \frac{l\bar{Q}_{\text{max}}}{\bar{L}} \tag{19}$$

Based on Eq. (19), the solutions that can be implemented by a traffic engineer at a planning and operational level to improve roundabout operations can be classified as follows:

- Increasing the maximum average flow around a roundabout, which can be achieved through innovative designs;
- Controlling the inflow into the roundabout, so that it does not exceed the maximum outflow; and
- Rerouting to reduce the average trip length, because the maximum outflow is inversely related to average trip length as shown in Eq. (18).

The last strategy is usually not implemented during normal conditions, but can prove extremely beneficial during special events. The first two strategies can be implemented at a planning and operational level, and are focused upon.

### Design-Based Strategy

Roundabout operations could also be improved by affecting $\bar{Q}_{\text{max}}$. As expected, and is observed in the earlier simulation results, the maximum average circulating flow is larger on two-lane roundabouts as compared with single-lane roundabouts, therefore resulting in a larger optimal inflow. Other geometrical interventions, such as adding flares to entry approaches, and providing dedicated lanes for drivers turning right when the number of drivers turning right is large, are also expected to increase the average circulating flow. The outflow can also be increased by reducing the average trip length, by rerouting drivers. These results provide an explanation for the findings made by Wang and Ruskin (2002). They found that the throughput is influenced by the topology of the roundabout and turning rates. The topology influences the maximum average circulating flow rate, and turning rates affect the average trip length.

### Inflow-Based Strategy

In an existing roundabout with geometric constraints that do not allow for design and geometric interventions, the only possibility to improve roundabout operations is through metering the inflow to ensure that the total inflow does not exceed $l\bar{Q}_{\text{max}}/\bar{L}$, as described in Eq. (19). This can be achieved by having a signalized roundabout that meters vehicles into the roundabout based on the average circulating flow. Similar results could also be achieved by metering vehicles from an upstream intersection. If it would not be possible to use signals, reducing the capacity at entry approaches could also be used to ensure optimal inflows. The control can also be achieved through direction by law enforcement officials. In fact, the improvement in efficiency of roundabouts through metering could explain the observation by Al-Madani (2003) observation of better operations at police-controlled roundabouts compared with signalized intersections.

The maximum outflow can be achieved by ensuring that the total inflow into the roundabout is equal to the maximum outflow, given by Eq. (19). To ensure fairness, the inflow on each of the approaches can be determined based on the demand ratio, while ensuring that the total inflow is less than or equal to the maximum outflow. The concept of inflow control is tested on one- and two-lane roundabouts using microsimulation.

### One-Lane Roundabout

It should also be noted that due to the stochastic nature of traffic flow, the maximum average circulating flow is unstable. Due to slight fluctuation in the inflow, the number of vehicles would increase, resulting in eventual gridlock. To overcome this, an average circulating flow rate of 830 vehicles/h was determined, such that the inflow was high but did not belong to the unstable region. The point is encircled in Fig. 4. Based on earlier analysis, the ratio of average trip length to total length of the roundabout was 2.96, therefore the total outflow at the average circulating flow rate of 830 vehicles/h was 2,456 vehicles/h ($830 \times 2.96$). To ensure efficient operations, the total inflow was fixed at 2,456 vehicles/h, and the inflow from each approach was determined based on the proportions of the total demand in Fig. 2. The outflow was found to be approximately 2,443 vehicles/h.

This case was compared with the case in which the total inflow is considered to be 2,610 vehicles/h. The outflow for the case of higher total inflow was found to decrease by approximately 50%, due to gridlock, to 1,288 vehicles/h.

### Two-Lane Roundabout

As in the case of a single-lane roundabout, due to the stochastic nature of traffic flow, the maximum average circulating flow is unstable. Therefore, slight fluctuation in the inflow could increase the number of vehicles that enter the roundabout, and could eventually result in a gridlock. Hence, the average circulating flow rate was determined to be 1,760 vehicles/h for a two-lane roundabout. This ensured that the inflow was high, but was robust to any fluctuations in traffic inflow. This point is encircled in Fig. 8. Based on earlier analysis (Fig. 7), the ratio of average trip length to total length of the roundabout was 3.15, therefore the total outflow at the average circulating flow rate of 1,760 vehicles/h was 5,544 vehicles/h ($1{,}760 \times 3.15$). The total inflow was fixed at 5,544 vehicles/h, while the inflow from each approach was determined based on the proportions of the total demand in Fig. 6. The outflow was found to be approximately 5,505 vehicles/h. This case, when



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compared with the case in which the total inflow equal to 8,221 vehicles/h, was found to have a lower outflow equal to 4,343 vehicles/h.

## Conclusion

This research proposes a strategy to control inflow into roundabouts to ensure efficient operations. To develop this control strategy, a theoretical framework was formulated that better explained the impact of origin-destination flows, as well as the relationship between outflow, average trip length, and average circulating flows. Based on the theory, as expected the outflow from the roundabout was found to increase with increase in average circulating flow, and decrease with increase in average trip lengths, which are determined by the origin-destination flows. It was also found that the inflow into the roundabout should not exceed the maximum outflow, to maintain optimal operations.

It was found that the maximum average circulating flow could be used to describe the capacity of a roundabout. The maximum average circulating flow is a function of the geometry, configuration, and number of lanes of the roundabout, and is independent of the origin-destination flows. It is a measure of the quality of traffic at a roundabout, and is not affected by any endogenous characteristics of traffic.

The inflow control strategy proposed was based on ensuring that the total inflow into the roundabout was equal to the product of the maximum average circulating flow of the roundabout and the ratio of the average trip length and total lane length of the roundabout. Such a strategy can be implemented using signalized roundabouts, or having signals upstream that meter traffic into the roundabout.

The topology of the roundabout can significantly influence the maximum average circulating flow rate. As expected, a two-lane roundabout was found to have a larger maximum average circulating flow as compared with a single-lane roundabout. and turning rates affect the average trip length. Other geometrical factors such as having flares to entry approaches and having dedicated right turning lanes are also expected to increase the average circulating flow. Further studies are needed to characterize these effects.

Planners can use the average circulating flows as a measure of roundabout capacity, and can use these to design and develop efficient roundabouts. For existing roundabouts, engineers can utilize an inflow control strategy presented in this paper to maintain efficient traffic operations.

Future work is underway to study the characteristics for other roundabout configurations, and conduct field experiments to further study the impact of roundabout geometry and origin-destination flows. These findings will help planners and operations experts evaluate, design, and operate roundabouts efficiently.

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