Capacity evaluation of multi-lane traffic roundabout

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SUMMARY

The entry capacity at a traffic roundabout is typically evaluated for each entry approach, considering the circulating flow and geometric characteristics, e.g., the US highway capacity manual model and the UK Linear Regression model. These models are not appropriate for analyzing multi-lane roundabouts because they do not take into account the possible unequal traffic distribution between the circulating lanes. This paper introduces a lane-based methodology that evaluates the entry capacity for each individual lane while considering the traffic distribution on the circulating lanes. The arrival and circulating flows are formulated based on drivers’ lane choice patterns. We then modify and extend the formulae from existing models for the analysis of capacity of multi-lane roundabout. Based on the analysis, we show that higher capacity can be achieved when the utilization on the circulating lanes is more balanced. This result can lead to improved design and management techniques to increase the capacity of multi-lane roundabout. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: intersection capacity; traffic roundabout; multi-lane roundabout; lane use

1. INTRODUCTION

Traffic roundabout is an unsignalized junction where priority rules take the role of traffic signals by assigning rights-of-way among the conflicting traffic streams. Unlike traffic signal, wherein vehicle entrance to a junction is controlled by the allocation of green times (e.g., [1,2]), vehicles entering a roundabout must give way to vehicles already in the roundabout. Compared to signalized intersections, roundabouts are known to reduce both accident rate and accident severity because they have fewer conflict points and vehicles in a roundabout typically lower their speeds [3,4]. A further advantage of roundabout is that it can easily accommodate U-turn traffic. Indeed, many countries have adopted traffic roundabout as a way to manage the intersection traffic [5].

Evaluating the capacity of roundabout is an important element in the planning and design of such facilities. Due to the interactions between flows of different origin–destination pairs at a roundabout, capacity is conventionally evaluated for each entry arm of a roundabout. Entry capacity is defined as the maximum allowable inflow of an entry arm under a given amount of circulating flow. Because entering vehicles have to yield to circulating vehicles, entry capacity is generally a decreasing function of the circulating flow. The geometric characteristics of a roundabout and driver behavior, such as speed and lane choices, are other factors affecting the entry capacity.

The US Highway Capacity Manual’s (HCM) entry capacity model [6] is developed based on the gap acceptance theory. Vehicles waiting at entry are exposed to a series of gaps (i.e., headways) between the circulating vehicles, and they accept the first gap that is longer than or equal to their critical gap.

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Entry capacity is then formulated as a function of the circulating flow, the critical gap, and the follow-up time. This model, however, only applies to single-lane roundabouts. At a multi-lane roundabout, entrance to the roundabout requires yielding to multiple streams of circulating flows and the decision on gap acceptance is more complex.

The UK Linear Regression model [7], based on empirical results, expresses the entry capacity as a linear function of the circulating flow. Although the model was derived from a large set of field data including those of multi-lane roundabouts, bias is prone to arise if they are directly applied to multi-lane roundabouts, as the model does not explicitly specify the number of circulating lanes. The simplification in the Kimber model by grouping together all the circulating lanes as one overlooks the effect of drivers’ lane choices on entry. Clearly, drivers who choose to entry onto the outer circulating lane in a multi-lane roundabout face a different circulating flow as compared with those who choose to enter onto the inner circulating lane. This problem becomes important when the traffic on the inner circulating lane becomes substantial, as expected in more congested traffic.

In this paper, we introduce a methodology wherein the entry capacity is evaluated for each lane, taking into account the specific conflicting flows to be encountered by each entry lane. This is analogous to the lane-based method for isolated signalized junctions in which traffic movements on individual lanes are explicitly considered [8,9]. For each entry lane of the multi-lane roundabout, both the HCM model and the Kimber model are adapted to estimate the lane entry capacity. Different from the SIDRA software [10], which models the capacity of a roundabout based on a microscopic approach through drivers’ yielding and gap acceptance behaviors, this study follows a macroscopic approach to model the lane-by-lane capacity of a roundabout, which is simpler and hence computationally efficient.

One point to note is that this study considers driving on the left side of the road. Vehicles in a roundabout circulate in the clockwise direction. Drivers entering the roundabout must give way to the circulating traffic to their immediate right. This convention applies to Hong Kong, UK, Japan, etc. The case of driving on the right side of the road can be described as a mirror image of the discussion provided herein.

2. FORMULATION

While the methodology developed in this study can be applied to all sorts of multi-lane roundabouts, for simplicity and illustration purposes, we only consider the most common type of multi-lane roundabouts – the double-lane roundabout. A double-lane roundabout typically has two entry lanes in each entry arm, two circulating lanes, and two exit lanes, as shown by the four-arm example in Figure 1. In terminology, we differentiate the two entry and exit lanes by calling them the kerb-side

Figure 1. Four-arm double-lane roundabout and the four turning movements.
lane and the splitter-side lane. The kerb-side lane is located closer to the road edge (kerb, or curb) and is on the left-hand side from drivers’ perspective; the splitter-side lane is closer to the splitter island (or deflection island) and is on the right-hand side. The two circulating lanes are called, respectively, the outer lane (closer to kerb) and the inner lane (closer to the central island).

2.1. Drivers’ lane choices at multi-lane roundabouts

Drivers’ lane choices at a multi-lane roundabout are complex. Unlike the case of a single-lane roundabout, where the only rule is to yield to vehicles approaching from the right and then circulate to the left, multi-lane roundabouts involve decisions on lane choices. Lane choice is indeed necessary at several decision points: entering, circulating, and exiting. A typical choice set for four-arm double-lane roundabouts is listed in Table I, as recommended by Hong Kong Road Users’ Code [11]. At entering and circulating, the left-turn (L) and going-through (T) traffic streams are recommended to take the kerb-side entry lane and the outer circulating lane, while the right-turn (R) and U-turn traffic streams to take the splitter-side entry lane and the inner circulating lane. Upon exit, all traffic streams are recommended to take the kerb-side exit lane, even though the T, R, and U traffic streams may also take the splitter-side exit lane with caution. So, the only thing clear is that left turns should use the kerb-side entry lane, the outer circulating lane, and the kerb-side exit lane. Other traffic streams are allowed to have different degrees of flexibility in choosing the entry, circulating, and exit lanes.

To develop an understanding of drivers’ actual lane choices, we conducted a series of field surveys on a four-arm double-lane roundabout located in a residential area in Hong Kong. Drivers’ lane choices at entering, circulating, and exiting were recorded for six 1-hour periods with different hourly volumes. The results, depicted in Table II, show that while most drivers comply with the recommended lane choices as in Table I, a sizeable proportion of drivers chooses differently from the recommendations. As we will show in the next section, these drivers’ lane choices have significant impacts on the ultimate capacity of a multi-lane traffic roundabout.

From the results, it is worth noting that drivers’ lane choices are made in a fashion that can be described as “habitual.” This is supported by the observation that only small variations of lane choices were recorded across the different survey times with different volumes, as shown in Table II. This result suggests that drivers’ lane choices at the aggregate level are somewhat independent of the actual traffic conditions. In other words, lane choices at the aggregate level are decided habitually rather than adaptively. An adaptive choice should show different proportions of lane use according to the prevalent traffic conditions. However, no consistent pattern is observed in Table II as to whether the uses of the kerb-side entry lane, the outer circulating lane, or the kerb-side exit lane, increase or decrease with the traffic volume.

2.2. Lane-by-lane flow modeling

For traffic flow of the same movement from a given approach, among a multitude of possible lane usages, we simplify the lane choices on a roundabout into only two types: a proportion of drivers enters from the kerb-side entry lane, circulates on the outer circulating lane, and exits to the kerb-side exit lane (lane choice $K$); while the rest of them enters from the splitter-side lane, circulate on the inner lane, and exits to the kerb-side lane (lane choice $S$). This simplification represents the majority of drivers’ lane choices and simplifies the analysis.

Table I. Recommended lane choices at four-arm double-lane roundabouts.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Entering</th>
<th>Circulating</th>
<th>Exiting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning left (L)</td>
<td>Kerb-side</td>
<td>Outer</td>
<td>Kerb-side</td>
</tr>
<tr>
<td>Going through (T)</td>
<td>Kerb-side (Splitter-side)*</td>
<td>Outer (Inner)</td>
<td>Kerb-side (Splitter-side)</td>
</tr>
<tr>
<td>Turning right (R)</td>
<td>Splitter-side</td>
<td>Inner</td>
<td>Kerb-side (Splitter-side)</td>
</tr>
<tr>
<td>U-turn (U)</td>
<td>Splitter-side</td>
<td>Inner</td>
<td>Kerb-side (Splitter-side)</td>
</tr>
</tbody>
</table>

*Lane choices listed in parentheses are also recommended but must be carried out with caution.
Consider a roundabout with \( n \) (typically, \( n = 3 \) or 4) arms (or approaches), there exist \( n^2 \) pairs of origin–destination movements. Each arm of a roundabout is sequentially labeled, arm 1, arm 2, \ldots, till arm \( n \) in the clockwise order. We denote \( D_{n \times n} \) as the demand matrix with \( D_{ij} \) representing the demand flow entering the roundabout from arm \( i \) and exiting to arm \( j \). For demand \( D_{ij} \), a proportion of \( \alpha_{ij} \in [0, 1] \) makes lane choice \( K \) whereas a proportion of \( (1 - \alpha_{ij}) \in [0, 1] \) makes lane choice \( S \).

Let \( m \) be the number of movements in a roundabout. For example, in a typical four-arm roundabout, there are four movements, left turn, straight, and right- and U-turns. In general, the number of movements in a roundabout coincides with the number of arms, i.e., \( m = n \). We denote the left-turn traffic, which exit at the next arm, as the 1st movement, and the \( k \)th movement as the one exiting at the \( k \)th arm after arm \( i \) in the clockwise direction. In this order, the last or \( n \)th movement represents the U-turn traffic, which exit at the same arm \( i \). For the example of a four-arm roundabout as in Figure 1, the 1st movement represents left turn (L), the 2nd going through (T), the 3rd right turn (R), and the 4th U-turn (U). We define the relative turning function as:

\[
d(k, i) = \text{mod}(i + k - 1, n) + 1,
\]

where \( \text{mod}(p, q) = p - \text{int}(p/q)q \) is the remainder function. Physically, for the traffic entering at arm \( i \), \( d(k, i) \) represents its exit arm after making the \( k \)th movement in the roundabout. For example, in a roundabout with four arms, i.e., \( n = 4 \), the right-turn traffic (i.e., \( k = 3 \)) that enter from arm \( i = 2 \) will exit to the arm of \( d(3, 2) = \text{mod}(2 + 3 - 1, 4) + 1 = 1 \) or \( i = 1 \).

In the analysis of capacity, we separate the flows on the circulating lanes as well as on the entry lanes in order to incorporate the channelization effect. As shown in Figure 2, the kerb-side and splitter-side entry lanes are measured separately. Because of the simplification in lane choices, the traffic stream of lane choice \( K \) waits on the kerb-side lane for an acceptable gap and circulates on the outer lane until exit; the traffic stream of lane choice \( S \) waits on the splitter-side lane and circulates on the inner lane until changing to the outer lane when exiting at the upcoming arm (e.g., the right- and U-turn movements in Figure 1).

The entry flow on the kerb-side lane must yield to the circulating flow on the outer lane but not to the circulating flow on the inner lane. This is because all vehicles exiting at the next arm are assumed to have changed to the outer lane and vehicles remaining on the inner lane are those who will be exiting further down after the next arm. Therefore, the circulating flow on the inner lane does not conflict with the entry flow on the kerb-side lane; only the circulating flow on the outer lane does. The entry flow on the splitter-side lane, on the other hand, must yield to the circulating flows on both the inner and outer lanes. The conflicting flow is, therefore, the sum of the two circulating flows.

<table>
<thead>
<tr>
<th>Survey</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume/hour</td>
<td>832</td>
<td>814</td>
<td>1092</td>
<td>1002</td>
<td>1040</td>
<td>972</td>
</tr>
<tr>
<td>Percentage of entering on the kerb-side entry lane (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>98</td>
<td>98</td>
<td>95</td>
<td>98</td>
<td>96</td>
<td>97</td>
</tr>
<tr>
<td>T</td>
<td>68</td>
<td>64</td>
<td>65</td>
<td>69</td>
<td>66</td>
<td>58</td>
</tr>
<tr>
<td>R</td>
<td>26</td>
<td>26</td>
<td>35</td>
<td>40</td>
<td>28</td>
<td>21</td>
</tr>
<tr>
<td>U</td>
<td>9</td>
<td>4</td>
<td>5</td>
<td>12</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>Percentage of circulating on the outer circulating lane (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>100</td>
<td>98</td>
<td>98</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>T</td>
<td>74</td>
<td>64</td>
<td>64</td>
<td>76</td>
<td>63</td>
<td>50</td>
</tr>
<tr>
<td>R</td>
<td>25</td>
<td>20</td>
<td>27</td>
<td>34</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>U</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Percentage of exiting on the kerb-side exit lane (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>99</td>
<td>97</td>
<td>97</td>
<td>98</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>T</td>
<td>81</td>
<td>82</td>
<td>78</td>
<td>80</td>
<td>80</td>
<td>83</td>
</tr>
<tr>
<td>R</td>
<td>72</td>
<td>71</td>
<td>69</td>
<td>70</td>
<td>67</td>
<td>69</td>
</tr>
<tr>
<td>U</td>
<td>78</td>
<td>72</td>
<td>83</td>
<td>89</td>
<td>86</td>
<td>89</td>
</tr>
</tbody>
</table>
2.3. Arrivals and conflicts

At arm $i$, the arrivals on the kerb-side lane, $q^K_a(i)$, consists of all the demands that are making the lane choice $K$. The rest of the demands constitutes the arrivals on the splitter-side lane, $q^S_a(i)$. That is

$$q^K_a(i) = \sum_{k=1}^{n} \alpha_{i,d(k,i)} D_{i,d(k,i)} = \sum_{j=1}^{n} \alpha_{i,j} D_{i,j} \quad (1)$$

$$q^S_a(i) = \sum_{k=1}^{n} [1 - \alpha_{i,d(k,i)}] D_{i,d(k,i)} = \sum_{j=1}^{n} [1 - \alpha_{i,j}] D_{i,j} \quad (2)$$

For the traffic flow waiting to enter on the kerb-side entry lane of arm $i$ (i.e., $q^K_a(i)$), the conflicting flow $q^C_a(i)$ includes all the circulating vehicles on the outer lane, i.e.

$$q^C_a(i) = q^O_a(i) \quad (3)$$

It can be written as:

$$q^C_a(i) = \sum_{k=1}^{n} \sum_{l=n-k+1}^{n} \alpha_{d(k,i),d[l,d(k,i)]} D_{d(k,i),d[l,d(k,i)]}$$

$$+ \sum_{k=1}^{n} [1 - \alpha_{d(k,i),d[n-k+1,d(k,i)]}] D_{d(k,i),d[n-k+1,d(k,i)]} \quad (4)$$

The first term on the right-hand side of (4) sums all the $K$-choice circulating flows that will cross arm $i$. Because they are circulating on the outer lane, they contribute to the conflicting flow of $q^C_a(i)$. The second term sums all the $S$-choice flows, originally circulating on the inner lane, change to the outer lane in preparation for exit at the next arm $d(1,i)$. Hence, they conflict with the flow $q^K_a(i)$ entering from arm $i$, the arm immediately before arm $d(1,i)$.

For the traffic flow waiting to enter on the splitter-side entry lane (i.e., $q^S_a(i)$), it must give way to the circulating vehicles on both the inner and outer lanes. The conflicting flow, $q^C_a(i)$, includes circulating vehicles on both the outer lane and the inner lane, i.e.

$$q^C_a(i) = q^O_a(i) + q^I_a(i) \quad (5)$$

It is given by the sum of all vehicles that will cross arm $i$ in their circulating, i.e.

$$q^C_a(i) = \sum_{k=1}^{n} \sum_{l=n-k+1}^{n} D_{d(k,i),d[l,d(k,i)]} \quad (6)$$

It should be noted that the conflicting flow Equations (4) and (6) have already assumed that all the arrival flows are guaranteed entry, i.e., the capacity constraints are satisfied. If this assumption fails to hold, an iterative procedure must be adopted to estimate the volume of the circulating flows.

3. CAPACITY ANALYSIS

The capacity analysis for traffic roundabout is conventionally conducted for each individual approach, as in both the HCM model and Kimber model (approach entry capacity). In this study, we adapt and refine the HCM and Kimber approaches for evaluating the capacity of each individual entry lane based on the arrivals and conflicts encountered as discussed in Section 2.3.
The entry capacity $Q_E$ is defined as the maximum inflow possible from the entry under a given circulating flow. The entry capacity decreases as the circulating flow increases, since there are then fewer chances for the waiting vehicles to enter the circulation. When the entry opportunities do present themselves, the number of vehicles able to enter depends on the characteristics of driver behavior and roundabout geometry. The entry capacity defines the maximum flow that can be accommodated. In practice, it may not be desirable to operate a roundabout at its capacity; thus, we may also define the measure $p$ as the maximum acceptable degree of saturation (DoS), such that

$$q_a \leq pQ_E$$  \hspace{1cm} (7)

In essence, (7) provides a practical bound in order to maintain an acceptable level of service.

3.1. The highway capacity manual model

The HCM model expresses the entry capacity $Q_E$ as a function of the conflicting flow $q_c$:

$$Q_E = \frac{q_c \exp\left(-q_c t_c/3600\right)}{1 - \exp\left(-q_c t_f/3600\right)}$$  \hspace{1cm} (8)

where $t_c$ is the critical gap in the gap acceptance model and $t_f$ is the follow-up time. Typical values for $t_c$ and $t_f$ range from 4.1 to 4.6 and 2.6 to 3.1 s, respectively. Derived from the gap acceptance theory, the HCM formula gives the resulting entry capacity based on drivers’ gap acceptance behavior when exposed to a single stream of circulating flow, wherein the arrival of vehicles in the circulating flow follows a Poisson process and the inter-arrival times are exponentially distributed.

Although the HCM model is applicable to single-lane roundabouts only, the same Equation (8) can be applied for multi-lane roundabouts by separating the conflicts to be encountered in each entry lane. Under the lane by lane scheme, the same argument for the Poisson process holds. For the kerb-side entry lane, this is obvious as the conflicting flow is in a single stream. For the splitter-side entry lane, the conflicting flow consists of two streams, one on the inner circulating lane, the other on the outer circulating lane. An acceptable gap is the concurrence of two acceptable gaps in the two streams, which is equivalent to an acceptable gap in the combined stream. If the independent Poisson process is assumed for the arrivals in the two streams, then the arrivals in the combined stream also follow a Poisson process whose density is the sum of the densities of the two streams. Therefore we have the following lane entry capacity formulae:

$$Q^K_E = \frac{q_c^K \exp\left(-q_c^K t_c^K/3600\right)}{1 - \exp\left(-q_c^K t_f^K/3600\right)}$$  \hspace{1cm} (9)

$$Q^S_E = \frac{q_c^S \exp\left(-q_c^S t_c^S/3600\right)}{1 - \exp\left(-q_c^S t_f^S/3600\right)}$$  \hspace{1cm} (10)

where the critical gap and the follow-up time are also lane specific.

3.2. The Kimber model

The Kimber model expresses the entry capacity of an individual approach as a linear function of the circulating flow:

$$Q_E = \max\{K[F - f_c q_c], 0\}.$$  \hspace{1cm} (11)
The values of $K$, $F$, and $f_c$ are determined by:

\[
K = 1 - 0.00347(\phi - 30) - 0.978(1/r - 0.05)
\]

\[
F = 303x_2
\]

\[
f_c = 0.210t_D(1 + 0.2x_2)
\]

\[
t_D = 1 + \frac{0.5}{1 + \exp \left( \frac{D-60}{10} \right)}
\]

\[
x_2 = v + \frac{e - v}{1 + 2s}
\]

\[
s = \frac{1.6(e - v)}{L}
\]

where $e$ is the entry width (m), $v$ the approach half width (m), $L$ the effective flare length (m), $D$ the inscribed circle diameter (m), $r$ the entry radius (m), and $\phi$ the entry angle (°).

The Kimber model does not consider the effect of lane choice patterns. If these formulae are directly applied to a multi-lane roundabout, the output of the approach entry capacity remains the same regardless of what the lane choices may be. Therefore, the Kimber model should not be directly applied to multi-lane roundabouts. However, by specifically accounting for the lane by lane usage and conflicts, or in effect, converting the merge effect of multi-lane roundabouts to that of single-lane roundabouts, one can still take advantage of the Kimber model. Nevertheless, the geometric characteristics of the double-lane roundabout need to be coded. In the end, the entry capacity can be calculated separately for each entry lane:

\[
Q^K_E = \max \{ K^K[F^K - f^K_c q^K_c], 0 \}
\]

\[
Q^S_E = \max \{ K^S[F^S - f^S_c q^S_c], 0 \}
\]

### 3.3. Roundabout performance

The entry capacity is evaluated for each entry approach or entry lane. To determine the ultimate capacity of a roundabout, we use the concept of reserve capacity [12]. In this approach, a uniform multiplier $\mu$ is applied to all the approach volumes $\{D_{ij}\}$ or in vector form $D$. We then maximize the multiplier $\mu$ subject to the constraint of acceptable DoS depicted in (7), expressed as:

\[
\begin{align*}
\max \mu \\
\text{s.t.} \\
q^K_E(\mu D) &\leq pQ^K_E(\mu D) \\
q^S_E(\mu D) &\leq pQ^S_E(\mu D)
\end{align*}
\]

where the lane arrival flow and the lane entry capacity are functions of the OD demand as depicted in (1)–(6). In essence, what (14) does is to find the maximum multiplier that can be accommodated while not violating any of the DoS constraints. One can express the solution of (14) to be:

\[
\mu \leq \mu^K_{\max} = \max \{ \mu : q^K_E(\mu D) \leq pQ^K_E(\mu D) \}
\]

and

\[
\mu \leq \mu^S_{\max} = \max \{ \mu : q^S_E(\mu D) \leq pQ^S_E(\mu D) \}
\]

To maintain an acceptable level of service, the performance constraint must be satisfied on both lanes of all approaches, which gives

\[
\mu \leq \mu_{\max} = \min_{i=1,2,...,n} \{ \mu^K_{\max}(i), \mu^S_{\max}(i) \}
\]
Here $\mu_{\text{max}}$ gives the maximum multiplier for the whole roundabout. If the demand is allowed to grow uniformly on all OD pairs, we can then define the practical capacity of the roundabout as:

$$Q = \mu_{\text{max}} \sum_{i=1}^{n} \sum_{j=1}^{n} D_{ij}$$

(18)

The capacity reserve is then defined as:

$$Q_{\text{Res}} = (\mu_{\text{max}} - 1) \sum_{i=1}^{n} \sum_{j=1}^{n} D_{ij}$$

(19)

For the case of using the HCM model, we need to substitute (9) and (10) into (14) and solve the maximization program directly. On the other hand, for the case of using the Kimber model, due to its linearity, the multiplier bound can be derived in the following closed form solution.

$$\mu \leq \mu_{\text{max}} = \min_{i=1,2,...,n} \left\{ \min \left[ \frac{pK^K(i)pK^K(i)}{q^K(i) + pK^K(i)f^K(i)q^K(i)}, \frac{pK^K(i)f^K(i)q^K(i)}{q^K(i) + pK^K(i)f^K(i)q^K(i)} \right] \right\}$$

(20)

### 4. NUMERICAL STUDY

To illustrate the lane-by-lane methodology proposed, we apply it to the four-arm double-lane roundabout studied in our field survey. For the purpose of determining the practical capacity, the maximum acceptable DoS, $p$, is set to be 0.85. Each arm has an arrival flow of 100 vehicles per hour, with the percentages of turning movements separated into three cases (see Table III). To simplify the numerical study, the arrivals at each arm are assumed to follow the same percentages of turning movements as depicted in Table III. The data in Case I were collected from the field survey, representing the actual traffic pattern. Cases II and III are specially created to represent more unbalanced turnings – Case II with predominant left turns and through traffic; Case III with predominant right- and U-turns.

For each of the three cases listed in Table III, three lane usage schemes, from (a) to (c), are studied. Table IV depicts the percentage of lane choice $K$ for different movements under each lane usage scheme. For example, in scheme (a), all left-turn traffic, half of through traffic, 20% of right-turn traffic, and 10% of U-turn traffic use the lane choice $K$. Scheme (a) represents the case wherein most drivers comply with the recommended lane choices of the road users’ code. In contrast, scheme (c) represents the case of drivers’ aversion against using the inner circulating lane – even for right- and U-turns. Scheme (b) is intermediate between schemes (a) and (c).

#### 4.1. Results of adapting the highway capacity manual model

<table>
<thead>
<tr>
<th>Case\movement</th>
<th>L (%)</th>
<th>T (%)</th>
<th>R (%)</th>
<th>U (%)</th>
<th>Sum (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I – field data</td>
<td>22</td>
<td>36</td>
<td>29</td>
<td>13</td>
<td>100</td>
</tr>
<tr>
<td>Case II – predominant left turns and through traffic</td>
<td>30</td>
<td>50</td>
<td>20</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Case III – predominant right- and U-turns</td>
<td>20</td>
<td>20</td>
<td>40</td>
<td>20</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scheme\movement</th>
<th>L</th>
<th>T</th>
<th>R</th>
<th>U</th>
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<tr>
<td>Scheme a</td>
<td>100</td>
<td>50</td>
<td>20</td>
<td>10</td>
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<tr>
<td>Scheme b</td>
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<td>50</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Scheme c</td>
<td>100</td>
<td>70</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Table III. The proportions of movements in the three cases.

Table IV. Percentages of lane choice $K$ for different movements under the three lane usage schemes.
The input data for the HCM model include the lane specific critical gap and follow-up time, which are listed in Table V, as estimated from the field observation. The results are shown in Table VI.

Comparing the three cases, the flow patterns with higher percentages of left turns and through movements (i.e., Case II) usually result in a higher capacity. Case II offers the highest capacity, as 80% of its traffic are either left turn or drive-through traffic, compared to 58% in Case I and 40% in Case III. This result is reasonable, because the increased number of drivers making U- or right-turns will travel further around the roundabout, conflicting with more entry flows and thus reducing the capacity \( Q \) of the roundabout. This result is echoed in the opposite manner for Case III, which has the highest percentages of right- and U-turns, resulting in the lowest capacity of the roundabout.

Other than turning percentages, the results clearly show that the lane usage scheme affects the roundabout capacity of the roundabout substantially. Take the example of case II in Table VI, the capacity under scheme (c) varies from the capacity under scheme (a) by a difference of up to about 20%. In Table VI, the scheme that produces the largest capacity is underlined. It is interesting to see from Table VI that the recommended lane usage scheme of the road users’ codes does not always produce the largest capacity. In fact, it is only good for Case II (with predominant left turns and through traffic). For the actual traffic pattern measured in this study (Case I), scheme (b) is the best, wherein a sizeable proportion of right- and U-turns takes the land choice L (i.e., use the kerb-side entry lane and outer circulating lane). Finally, for Case III (with predominant right- and U-turns), scheme (c) (with 50% of right- and U-turns use the land choice L) produces the highest capacity, even though the differences among the three schemes are relatively small.

In Table VI, the left (right) shaded column indicates the DoS of the kerb-side (splitter-side) entry lane. As we set the maximum acceptable DoS to be 0.85, the capacity occurs when the DoS of any entry lane first reaches 0.85. In relating the DoS of the entry lanes and the lane usage scheme, we find that the maximum capacity for each case always occur when the resultant DoS of the two entry lanes are closest to each other, as shown in the last column of Table VI which calculates the DoS difference between the two entry lanes. This result indicates that a more balanced distribution of flows at the entry lane produces a higher capacity for the roundabout. For a specific flow pattern, there exists a different optimal lane usage scheme that gives the highest capacity. This result may be useful for the devising of dynamic lane usage schemes to optimize the capacity of roundabout.

4.2. Results of adapting the Kimber model

The input data for the Kimber model are listed in Table VII. The roundabout representation specified by the original Kimber model, which only applies to single-lane roundabout, needs to be adjusted to accommodate double-lane roundabout. Specifically, the entry width and approach width for the kerb-
side entry lane and the inscribed diameter for the right entry lane are to be measured from the actual geometry of the double-lane roundabout, as shown in Table VII. For the capacity calculation, like the case of the HCM model, we set the maximum acceptable DoS to be 0.85 for each entry lane.

The capacity results are shown in Table VIII. The results and patterns are surprisingly close to those of using the HCM model as shown in Table VI. Both models indicate the same optimal lane usage scheme in each of the three cases that gives rise to the highest capacity (Table IX). Both models also produce similar estimates of the capacities and the differences in DoS between the entry lanes. The surprisingly good consistency in results certainly adds credibility to the lane-by-lane analysis introduced in this study, showing that either model can be used for this purpose, with similar outputs.

### 5. CONCLUDING REMARKS

This paper proposed a lane-by-lane methodology to analyze the capacity of multi-lane roundabouts. The entry capacity is evaluated for each individual entry lane rather than grouping all the entry lanes into one single approach. Once this lane-based approach is developed, it can be used to study the effects of drivers’ lane choices on roundabout capacity. Using this methodology as a platform, we embedded both the HCM and Kimber models as options for the analysis of capacity of multi-lane roundabout.

The results indicated that both turning proportions and drivers’ lane usage within a roundabout have substantial impacts on the capacity of traffic roundabout. Ignoring the aspect of drivers’ lane choices could lead to substantial errors in estimating roundabout capacity. The results also showed that a more balanced usage of the entry and circulating lanes was critical in increasing the capacity of roundabout.
Unfortunately, there is no fixed lane usage scheme that always produces the highest capacity. Rather, the lane usage scheme that gives rise to the maximum capacity depends on the turning proportions. Nevertheless, developing this understanding is important, as it may lead to better designs, such as through lane markings and guide signs [13], so as to encourage a lane usage pattern that is more robust or appropriate for the traffic at hand.

6. LIST OF SYMBOLS

\( \alpha_{i,j} \) proportion at \( D_{i,j} \) making lane choice \( K \)

\( D_{i,j} \) traffic flow entering the roundabout at arm \( i \) and exiting to arm \( j \)

\( p \) maximum acceptable DoS

\( Q \) practical capacity: maximum entry flow under uniform growth

\( Q^{E}_{K} \) entry capacity on the kerb-side lane

\( Q^{E}_{S} \) entry capacity on the splitter-side lane

\( Q_{\text{res}} \) capacity reserve

\( q^{E}_{K}(i) \) arrival flow on the kerb-side lane of arm \( i \)

\( q^{E}_{S}(i) \) arrival flow on the splitter-side lane of arm \( i \)

\( q^{C}_{K}(i) \) circulating flow on the inner lane at arm \( i \)

\( q^{C}_{O}(i) \) circulating flow on the outer lane at arm \( i \)

\( q^{C}_{S}(i) \) conflicting flow for entry at the splitter-side lane of arm \( i \)

\( q^{C}_{S}(i) \) conflicting flow for entry at the kerb-side lane of arm \( i \)

\( \mu \) uniform flow multiplier

\( \mu_{\text{max}} \) maximum flow multiplier under acceptable DoS

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