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Estimation of Entry Capacity for Single-lane Modern Roundabouts: A Case Study in Queensland, Australia

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Abstract

Single-lane modern roundabouts are one of the most important intersection types in suburbs of Australia. It is therefore important to estimate their entry capacities. In this case study, we firstly propose an analytical model based on the gap acceptance theory by incorporating the effects of the exiting vehicles. It then proceeds to carry out a scenario analysis to assess the effects of the exiting indicators. This is followed by the discussions of the applicability of the proposed model. The results show that the transport authorities need to strictly enforce the use of indicators before exiting in order to achieve higher capacity.

Key words: Roundabout; Entry capacity; Gap acceptance theory; Conflicting circulating flow.

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INTRODUCTION

A roundabout is a type of circular intersection or junction in which road traffic is slowed and flows almost continuously in one direction around a central island to several exits onto the various intersecting roads. As pointed out by Bie et al. (2008), unlike a signalized intersection, wherein traffic streams are controlled by the traffic signal, vehicles must follow the give way rules to enter a roundabout. The direction of traffic flow is either clockwise for left-side driving or anticlockwise for right-side driving. Since all vehicles are regulated to travel along with the same direction, number of conflicting points is significantly reduced (Wong et al., 2012). Further, the drivers usually slow down the vehicles' speed thanks to the impact of "give way" rules and the roundabout curves (Al-Masaeid, 1999). The roundabout is therefore considered as a safer intersection type compared to signalized intersections, in terms of both frequency and severity of accidents. A roundabout can also reduce the delay (for low traffic conditions) and thus decrease pollutant emissions (Hoglund, 1994).

Various studies have been carried out to estimate the capacity of roundabouts (e.g. Wong, 1996; Bie et al., 2010; Diah et al., 2011). The well-known *Highway Capacity Manual* (HCM) model is derived based on the gap acceptance theory (TRB, 2000). Another representative method is the *Federal Highway Administration* (FHWA) method based on empirical linear regression analysis (FHWA, 2000). So far, the HCM model is the most widely used analytical model (Tanyel et al., 2007; Dixit, 2012). The model is to estimate the entry capacity (the maximum possible entry flow on condition that the circulating flow remains unchanged) of an analyzed roundabout approach analytically. The critical gap (τ) and follow-up time (τ') are the two important concepts in the model. In general, the assumptions made in the HCM method are summarized as: 1) the headways (or gaps) of circulating flows are exponentially distributed random variables; 2) there are non-exhaustive vehicles queuing in the analyzed approach; 3) circulating flows are calculated by summing up all the conflicting flows from different approaches; and 4) all drivers' decision making process could be modeled as

$$n = \begin{cases} 0; \text{ if } t < \tau \\ i; \text{ if } \tau + (i-1)\tau' \le t < \tau + i\tau' \end{cases} \quad (1)$$

where *n* is the number of vehicles being able to enter a roundabout given a gap *t*.

Although the HCM model is theoretically sound, it ignores the effects of exiting vehicles on the entry capacity. In reality, the HCM model treats exiting vehicles as non-existent ones. Some scholars have already realized this problem (e.g. Troutbeck, 1984; TRB, 2007&2010; Zheng et al., 2011). For example, Hagring (2001) showed that the proportion of exiting vehicles has a significant impact on the entry capacity and indicated that the critical gaps might be overestimated if the exiting vehicles are not taken into account. Mereszczak et al. (2006) showed that the capacity at single-lane roundabouts was underestimated if the effect of exiting vehicles was not considered. Indeed, the exiting vehicles play an important role for the entry capacity of a roundabout. In reality, the effect of exiting vehicles has been implicitly taken into account to design the width of a splitter island so as to provide enough separation between the exiting vehicles and the entry flow (TRB, 2007).

The roundabout has become an increasingly popular intersection type in Australia, especially for suburbia with relatively low traffic volume (Akcelik, 2008). For example, over 90% intersections in Pacific Pines, a new suburb in Queensland, are modern roundabouts. In Queensland, all the exiting vehicles (from roundabouts) are required to indicate left before exiting. From our field survey for 19 single-lane modern roundabouts, the waiting vehicles could immediately (in an average of 1.4 seconds) enter the roundabout after exiting vehicle turn their indicators on (usually more than 1.4 seconds before the actual turning movements). In other words, a waiting vehicle may not necessarily wait for a critical gap if an exiting vehicle shows up.

In this paper, we propose a novel model to analyze the effects of exiting vehicles based on the gap acceptance theory. This model could better estimate the roundabout capacity than the HCM 2000 method. Based on the proposed model, a scenario analysis is carried out to evaluate influence of one important traffic rule – *indicating before exiting*.

THE HCM MODEL

In the HCM manual (TRB, 2000), the entry capacity at a roundabout is estimated by using gap acceptance theory with the basic parameters of critical gap and follow-up time. The entry capacity of a roundabout approach is estimated by

$$c_a = v_c \times \frac{\exp\left(-v_c \tau / 3600\right)}{1 - \exp\left(-v_c \tau' / 3600\right)} \tag{2}$$

where c_a is the capacity of approach *a* (veh/h); v_c is the conflicting circulating traffic (veh/h); τ and τ' are critical gap and follow-up time (s), respectively; $\frac{\exp\left(-v_c \tau / 3600\right)}{1 - \exp\left(-v_c \tau' / 3600\right)}$ is the expected number of vehicles that could enter the roundabout from this approach for one gap (derived by expectation theory by assuming there are non-exhaustive vehicles queuing in the analyzed approach).

According to eq. (2), the entry capacity of a roundabout approach is determined by the conflicting circulating traffic flow, critical gap, and follow-up time. The critical gap and follow-up time could be calibrated from field survey. It should be pointed out that different roundabouts should have distinct critical gap and follow-up time, namely, the two parameters are affected by the roundabout geometry (e.g. width of the splitter island). As for the conflicting circulating flow, the HCM (TRB, 2000) gives an approach to convert the turning movements into the circulating flow (in Page 17-47). As can be seen in Figure 1, each approach has 4 turning movements: left turn, straight, right turn, and U turn. According to HCM (TRB, 2000), the circulating flow could be calculated by summing up conflicting turning traffic from various approaches. For example, circulating flow at Arm 1 (v_c) is $v_8 + v_{11} + v_{12} + v_{14} + v_{15} + v_{16}$, which consists of the U turn flow of Approach 2, right turn and U turn flows of Approach 3, and straight, right turn, and U turn flows of Approach 4.

(Figure 1 is inserted here)

The NEW ROUNDABOUT CAPACITY MODEL

Model Development

In the HCM approach, the left turn flow v_{13} of Approach 4, straight flow v_{10} of Approach 3, right turn flow v_7 of Approach 2, and U turn flow v_4 of Approach 1 are not considered as circulating flow at Arm 1, and hence are irrelevant of the capacity of Arm 1. In reality, as discussed in the introductory section, these exiting vehicles (with indicators on as required by the traffic regulations) at this arm could "*block*" the traffic behind them in a single-lane modern roundabout in Queensland. According to our field data for a single-lane roundabout in Queensland, all waiting vehicles immediately enter the roundabout (in an average of 1.4 seconds) after the exiting vehicles turn the indicators on. In other words, the vehicles waiting at Arm 1 could enter the roundabout under this kind of scenarios even if the gap is not acceptable, which would significantly affect the entry capacity of a roundabout. The exiting vehicles are very important for drivers to determine whether to enter a roundabout. Therefore, it would be impractical to neglect the effects of the exiting vehicles. In this study, an improved roundabout capacity model is developed to better model drivers' decision-making process.

In the new model, these exiting vehicles are included in the conflicting circulating flow and the new conflicting circulating flow is denoted as $v_{c'}$. Let ρ denote the proportion of these exiting vehicles out of circulating flow. Accordingly, the gaps could be categorized into two types: the gaps which exiting vehicles are involved (Type 1) and the gaps without the involvement of exiting vehicles (Type 2). Evidently, the probabilities of occurrence of Type 1 gaps and Type 2 gaps could be estimated by ρ and $1-\rho$, respectively. Let T_1 (s) and T_2 (s) denote the Type 1 and Type 2 gaps, respectively.

According to our field survey, the drivers tend to give way to exiting vehicles with their indicators off. In other words, the drivers may treat an exiting vehicle with its indicator off as a non-existing vehicle. In this regard, a gap involving in an exiting vehicle with its indicators off should be considered as a Type 2 gap. Accordingly, ρ should be estimated as the proportion of exiting vehicles with their indicators on. For all Type 1 gaps, number of vehicles being able to enter the roundabout could be formulated by

$$N_1 = \begin{cases} 1, \text{ if } T_1 < \tau \\ i+1, \text{ if } \tau + (i-1)\tau' \le T_1 < \tau + i\tau' \end{cases} \tag{3}$$

where τ and τ' are the critical gap and follow-up time, respectively. Thus, the expected number of vehicles (denoted by n_1) being able to enter the roundabout during a Type 1 gap could be calculated by

$$n_1 = E(N_1) = 1 \times P(T_1 < \tau) + \sum_{i=1}^{\infty} \left[(i+1) P(\tau + (i-1)\tau' \le T_1 < \tau + i\tau') \right] \quad (4)$$

Equivalently,

$$n_1 = 1 + \sum_{i=1}^{\infty} \left[iP(\tau + (i-1)\tau' \le T_1 < \tau + i\tau') \right] \quad (5)$$

Without loss of generality, the traffic volume is still assumed to be exponentially distributed, namely,

$$P(T_1 > t) = P(T_2 > t) = \exp(-v_{c'} t / 3600) \quad (6)$$

Then, the eq. (5) could be simplified as

$$n_1 = 1 + \frac{\exp(-v_{c'}\tau / 3600)}{1 - \exp(-v_{c'}\tau' / 3600)} \quad (7)$$

Similarly, for all the Type 2 gaps, the expected number of vehicles (n_2) being able to enter the roundabout could be estimated by

$$n_2 = \frac{\exp(-v_{c'}\tau / 3600)}{1 - \exp(-v_{c'}\tau' / 3600)} \quad (8)$$

Accordingly, the entry capacity for one hour could be estimated by

$$c' = v_{c'} \times \left[\rho \times n_1 + (1-\rho) \times n_2 \right] \quad (9)$$

By substituting eqs. (7) and (8) to eq. (9), we have

$$c' = v_{c'} \times \left[\rho + \frac{\exp(-v_{c'}\tau / 3600)}{1 - \exp(-v_{c'}\tau' / 3600)} \right] \quad (10)$$

Model Validation

To validate the new model, we propose a concept of at-capacity conflicting headway (ACCH) in this study. ACCH is defined as a headway between two consecutive conflicting vehicles (as defined in HCM 2000) that is not able to discharge all waiting vehicles at the analyzed approach. Namely, there is a long enough queue in the analyzed approach for measuring the maximum possible entry vehicles (i.e. capacity) for this type of headways. There might be exiting vehicles in between the prevailing conflicting vehicle and trailing conflicting vehicles. After watching the videos recorded at a roundabout in Sunnybank, Queensland, Australia, 22 ACCHs are observed in the east arm. The actual number of entry vehicles for each ACCH and number of exiting vehicles involved in each ACCH are also recorded. The critical gap and follow-up time for the analyzed approach are calibrated as 4.63 seconds and 2.51 seconds, respectively. Thus the numbers of entry vehicles estimated by the HCM method and the new method could also be calculated according to eqs. (1) and (3), respectively. As can be seen in Table 1, the new method is more accurate than the HCM model for 19 ACCHs and both methods give correct estimation for the other 3 ACCHs.

(Table 1 is inserted here)

According to Table 1, a total of 132 vehicles enter the roundabout during the 22 ACCHs (367.8 seconds), which is equivalent to a capacity of 1,292 vehs/hour. The numbers of conflicting and exiting vehicles are 22 (equivalently 215 vehs/hour) and 53 (equivalently 519 vehs/hour), respectively. The proportion of exiting vehicles is 0.71[2]. According to eqs. (2) and (10), the capacities estimated by HCM 2000 and the new model are 1,171 vehs/hour and 1,236 vehs/hour. The relative errors of HCM 2000 and the new model are 9.4% and 4.3%. Based on the analysis above, the proposed model outperforms the HCM 2000 model for this roundabout.

[2] For validation purpose, we intentionally choose an arm with high proportion of exiting vehicles as the results estimated by the two models would be the same if no exiting vehicle is involved. Please refer to Arm 4 in Table 2 for hourly traffic volume.

A CASE STUDY IN QUEENSLAND, AUSTRALIA

A Scenario Analysis

In Queensland, Australia, before exiting a roundabout, the drivers must indicate left as required by the traffic rules. The flow streams collected at the above-mentioned roundabout are presented in Table 2. By including the exiting vehicles, the conflicting circulating flow for the new model (the $v_{c'}$ in eq. (10)) is greater than that calculated by the HCM model (the v_c in eq. (2)). The corresponding headways at various arms are represented in Figure 2. Here we assume headways are exponentially distributed as HCM 2000.

(Table 2 is inserted here)

(Figure 2 is inserted here)

We calculate the ratio of indicating left (out of all vehicles exiting to their exit arms) based on the collected data and we further use the collected data to calibrate the critical gap and follow-up time for different approaches, detailed in Table 3.

(Table 3 is inserted here)

By comparing eqs. (2) and (10), there are two differences: 1) conflicting circulating flow ($v_{c'} > v_c$); (2) the extra capacity of the new model ($\rho v_{c'}$). For the new model, the gaps become smaller (due to the increase of circulating flow) but the expected entry capacity for a gap of a given size has an increase of ρ. Accordingly, due to the combined effects of the two differences, the HCM model may yield higher or lower results than the new model.

We further assume four scenarios as follows.

Scenario 1: City council has a proposal to connect a new freeway off-ramp to Arm 1 of the roundabout. Therefore, they want to estimate the entry capacity at Arm 1, assuming circulating flow remains unchanged.

Scenario 2: City council wants to change the signal timing of the signalized intersection adjacent to Arm 2, which would affect the traffic volume in Arm 2. Thus, they want to analyze the entry capacity at Arm 2, assuming traffic conditions in other arms remain unchanged.

Scenario 3: City council intends to build a shopping mall 5 kilometers north of the roundabout, which would lead to more traffic in Arm 3 (north arm). Consequently, they want to estimate the entry capacity at Arm 3, assuming traffic flows at other arms remain the same.

Scenario 4: City council plans to build a theme park 10 kilometers east of the roundabout, which would affect the traffic flow at Arm 4 (east arm). Thus they want to estimate the entry capacity of Arm 4, assuming the traffic flows of other arms remains unchanged.

The entry capacities under these four scenarios are presented in Table 4. According to the results, the HCM model may overestimate the capacities of Scenarios 1 and 2, and underestimate the capacities of the other two scenarios.

(Table 4 is inserted here)

An Impact Analysis of Traffic Rules - *Indicating before Exiting*

Imagine two extreme scenarios: 1) all vehicles obey the traffic rules of indicating left before exiting; and 2) no vehicles obey the rule. According to the new model, the entry capacities of the four scenarios are shown in Table 5.

(Table 5 is inserted here)

As can be seen in Table 5, the entry capacity could decrease up to 63.8% if this regulation is not properly enforced. Accordingly, the transport authorities (e.g. Department of Transport and Main Roads in Queensland) need to strictly enforce this rule (e.g. by one demerit one violation), especially during peak hours.

Applicability of the Proposed Model

The most critical assumption for the proposed model is that the existence of such an exiting vehicle would always guarantee an entry opportunity. This might not be true for some small roundabouts or roundabouts which are able to accommodate very high-speed vehicles. Therefore, a field survey needs to be conducted to examine this point before applying this model to estimate the entry capacities for single-lane modern roundabouts. In reality, according to our field survey for more than 19 roundabouts cross 11 suburbs, this assumption is valid for most single-lane roundabouts in Queensland.

CONCLUSIONS AND RECOMMENDATIONS

In this paper, a more practical roundabout capacity model is developed by taking into account the impact of the exiting vehicles. The gaps are categorized into two types. The roundabout capacity model is developed for each type of gaps to better formulate whether a driver enters a roundabout. The results show that ignoring the effects of exiting vehicles may, under different traffic conditions, either underestimate (as discussed in Hagring (2001) and Mereszczak et al. (2006)) or overestimate (as Scenarios 1 and 2 in Table 3) the entry capacity of a roundabout arm. An impact analysis shows that the transport authorities need to strictly enforce the usage of indicators before exiting, especially during peak hour, in order to achieve higher capacity.

It should be pointed out the validation for the proposed model is based on one roundabout in a suburb in Australia. More data in other countries need to be collected to validate the proposed model. Further, compared to HCM 2000 model, the proposed model requires a new parameter – the proportion of exiting vehicles. In particular, for the design of roundabout at planning stage, this parameter is not readily available from the planning model.

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Figure 2: Headway distributions at the four arms

Table 1: At-capacity conflicting headways (ACCHs)

ACCHs (sec)	Number of exiting Vehicles	Observed number of entry vehicles	Number of entry vehicles by HCM 2000	Number of entry vehicles by new model
16.1	3	6	5	6
13.9	2	5	4	5
22.1	3	8	7	8
15.3	4	5	5	6
20.1	3	7	7	7
13.9	2	5	4	5
16.8	1	7	5	7
18.7	3	7	6	7
12.1	1	4	3	4
20.8	2	7	7	7
16.8	1	6	5	6
16.9	1	4	5	6
13.8	1	5	4	5
13.9	2	5	4	5
12.1	1	4	3	4
11.9	2	4	3	4
16.1	5	6	5	6
18.9	5	7	6	7
14.1	5	5	4	6
11.9	1	6	3	4
23.8	4	9	8	9
27.8	1	10	10	10

Table 2: Flow streams at a roundabout in Sunnybank, Queensland

Arm	Right turn (veh/hr)	Left turn (veh/hr)	Straight (veh/hr)	U-Turn (veh/hr)	Conflicting flow – HCM (veh/hr)	Conflicting flow – new model (veh/hr)
1	288	14	46	10	406	808
2	224	30	374	26	412	764
3	30	144	38	4	950	1066
4	36	130	282	28	332	1166

Table 3: Critical gaps, follow-up times, and ratio of indicating left for various approaches

Arm	Critical gap (s)	Follow-up time (s)	Ratio of indicating left (%)
1	4.36	2.31	74
2	4.57	2.47	67
3	5.03	2.26	71
4	4.63	2.51	73

Table 4: Capacity estimated by HCM model and the new model

Scenario	Capacity – HCM 200model (veh/hr)	Capacity – the new model (veh/hr)
1	1082.6	1048.2
2	991.7	945.9
3	560.8	575.1
4	1063.3	1081.5

Table 5: Impact analysis of traffic rules of indicating left before exiting

Scenario	Capacity – All vehicles obey (veh/hr)	Capacity – No vehicles obey (veh/hr)	Difference %
1	1152.6	750.6	34.9
2	1062.0	710.0	33.1
3	608.7	492.7	19.1
4	1306.6	472.6	63.8

Figure
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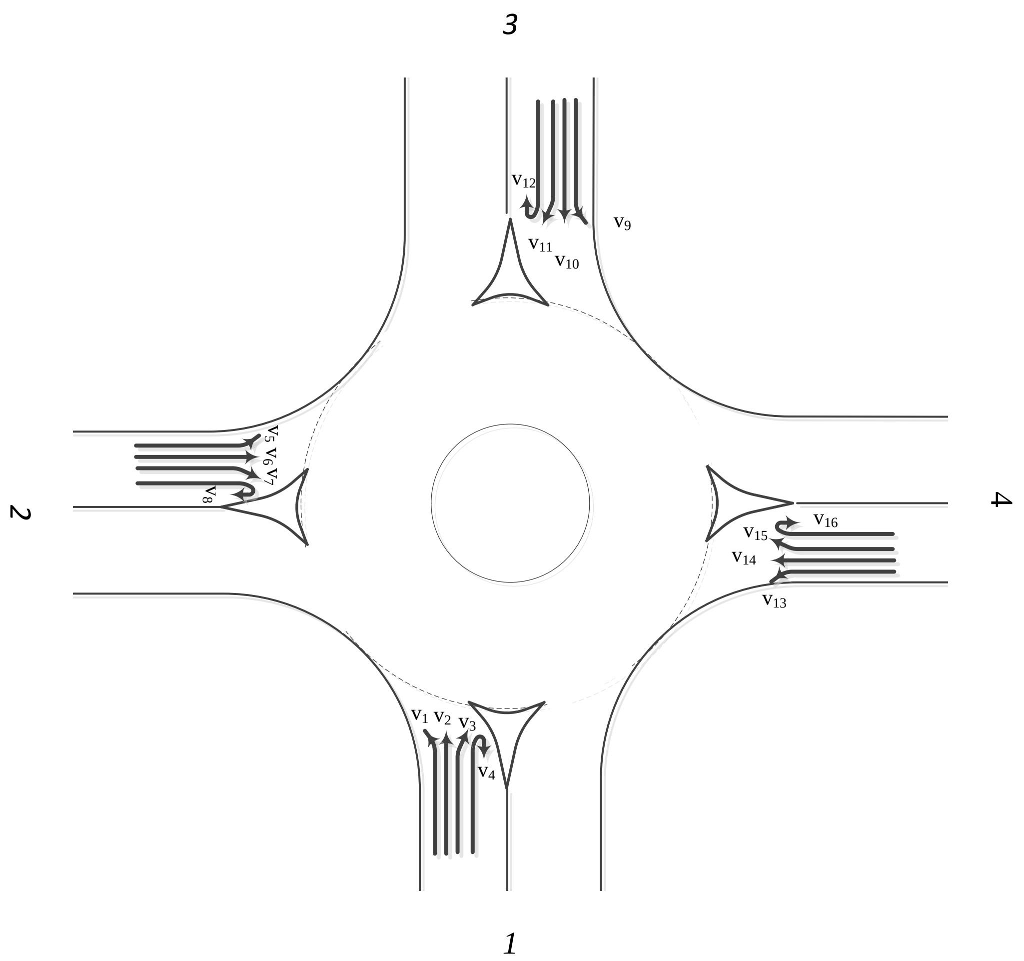

Figure 1: Flow streams in a roundabout (left driving system)

Figure 2
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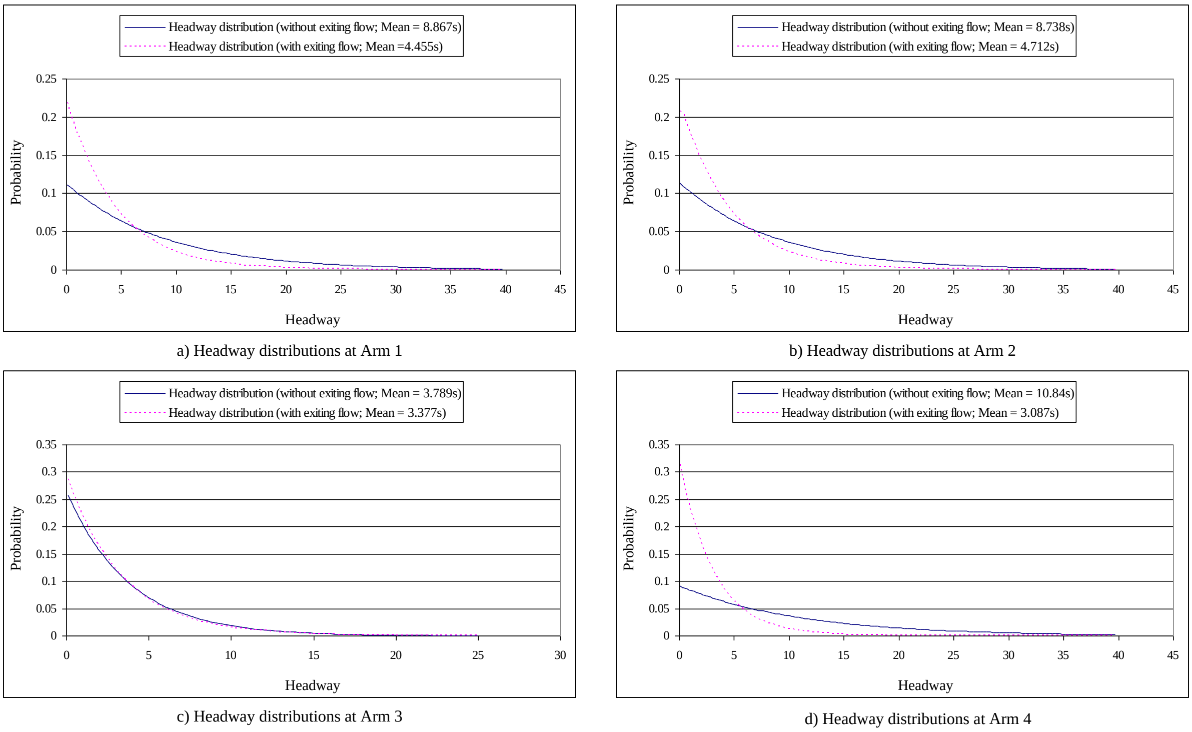

Figure 2: Headway distributions at the four arms