Empirical Estimation of Capacity for Roundabouts Using Adjusted Gap-Acceptance Parameters for Trucks

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This study examines the effect of heavy vehicles (trucks) on the entry capacity of roundabouts. Vehicle movements were observed at 11 roundabouts in Vermont, Wisconsin, and Ontario, Canada, and gap-acceptance parameters were estimated for cars and trucks separately. Consistent with previous studies, it was found that the critical headway and the follow-up time were longer for trucks than for cars. It was also found that the follow-up times for truck-involved vehicle-following cases were associated with the central island diameter and the entry angle. The gap-acceptance parameters for all entering vehicles were adjusted to a volume-weighted average of the gap-acceptance parameters for cars and trucks. The capacity was estimated with the existing capacity models with the adjusted gap-acceptance parameters and compared with the observed capacity at three roundabouts. It was found that the rate of reduction in the observed capacity with an increase in the circulating flow was lower at the roundabouts with a higher truck percentage. Also, the capacity models with the adjusted gap-acceptance parameters estimated the capacity more accurately than did the models with the unadjusted parameters. The study underscores the importance of considering the effect of trucks on capacity for the roundabouts with a high truck volume.

As roundabouts have become popular as a result of their operational efficiency and safety benefits, more roundabouts have been built on or near main highways to replace the existing signalized or stop-controlled intersections. However, because the volume of heavy vehicles (trucks) is higher at these roundabouts, the entry capacity is more likely to be affected by slower truck movements. The entry capacity is defined as the maximum number of vehicles that can enter the roundabout in unit time at a given entry leg for the flow in a circulating roadway. In general, the capacity decreases as the circulating (or conflicting) flow increases as a result of less opportunity for entry. In this study, a truck is defined as an 18-wheeler.

To account for the effect of trucks on the capacity, the capacity has been adjusted according to a truck's longer length and lower speed and the percentage of trucks. In the conventional approach, the capacity is adjusted for trucks by converting the number of vehicles to passenger car units (pcu's) (*1*). Because trucks are weighted higher than passenger cars, it is expected that the capacity will decrease more rapidly as the number of trucks in the circulating flow increases.

However, this adjustment method did not capture the effect of trucks on driver gap-acceptance behavior, which is essential to understand the roundabout operation affected by trucks (*2*). It was expected that a truck driver's gap-acceptance behavior would be different from a car driver's as the result of slower truck entry and longer gaps required by trucks.

Current gap-acceptance capacity models describe the capacity as a function of the circulating flow, the critical headway, and the follow-up time. The "critical headway" is defined as the minimum time gap between the circulating vehicles accepted by the entering vehicles. The "follow-up time" is defined as the time gap between two queued vehicles that enter the roundabout by using the same gap between the circulating vehicles. However, most past studies assume only single values of the critical gap and the follow-up time for cars and trucks.

Thus, the objectives of this study are to (*a*) identify the limitations of the existing roundabout capacity estimation methods with respect to truck traffic, (*b*) develop a method to take into account the effect of trucks on the capacity, and (*c*) evaluate the accuracy of capacity estimation with the proposed method by comparing with the observed capacity.

LITERATURE REVIEW

Gap-Acceptance Capacity Model

Roundabout capacity has been estimated by using various capacity models developed on the basis of gap-acceptance theory. These models assume that the headways (i.e., the time between consecutive vehicles passing the conflict point) of the circulating flow follow a certain distribution. Typically, the distribution follows an M1 (negative exponential), M2 (shifted negative exponential), or M3 (bunched exponential) distribution, as follows (*3*):

M1:

$$F(t) = 1 - e^{-\lambda t} \qquad \text{for } t \geq 0 \tag{1}$$

M2:

$$F(t) = 1 - e^{-\lambda(t-\Delta)} \qquad \text{for } t \geq \Delta \tag{2}$$

M3:

$$F(t) = 1 - \alpha \cdot e^{-\lambda(t-\Delta)} \qquad \text{for } t \geq \Delta \tag{3}$$

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where

$F(t)$ = cumulative probability that headway is less than or equal to t,
Δ = minimum headway between circulating vehicles (s),
λ = decay constant (s^{-1}), and
α = proportion of free vehicles (i.e., vehicle maneuver is not affected by the lead vehicle).

The decay constant λ is calculated with the following expression (*3*):

$$\lambda = \frac{q_c \cdot \alpha}{1 - q_c \Delta} \tag{4}$$

where q_c is the circulating flow (pcu/h). Troutbeck suggested that the proportion of free (unbunched) vehicles at a roundabout is dependent on the circulating flow as follows (*4*):

$$\alpha = 0.75\left(1 - \Delta \cdot q_c\right) \tag{5}$$

Alternatively, Akçelik suggested that α can be estimated by using the following equation (*5*):

$$\alpha = \max\left(\frac{\left(1 - \Delta \cdot q_c\right)}{1 - \left(1 - k_d\right)\Delta \cdot q_c}, 0.1\right) \tag{6}$$

where k_d is a constant. For two-lane roundabouts, k_d is 2.2 and Δ is set to 1 s (*5*). Equations 5 and 6 assume that the proportion of free vehicles decreases as the circulating flow increases as a result of shorter headways.

These distribution functions can be used in conjunction with gap-acceptance parameters to derive capacity estimation models. In these models, the capacity is expressed in an exponential function of the circulating flow. This expression is reasonable because the rate of reduction in the capacity generally decreases as the circulating flow increases and the capacity never reaches zero (*6*). For example, the capacity model adapted in the *Highway Capacity Manual* (HCM) 2000 uses an M1 distribution (Equation 1) and is described as follows (*1*):

$$C_e = \frac{3{,}600 \cdot q_c \cdot e^{-q_c t_c}}{1 - e^{-q_c t_f}} \tag{7}$$

where

C_e = entry capacity (pcu/h),
t_c = critical headway (s), and
t_f = follow-up time (s).

This capacity model was revised in HCM 2010 as follows (*7*):

$$C_e = \frac{3{,}600}{t_f} e^{-\left(\frac{t_c - 0.5 t_f}{3{,}600}\right) q_c} \tag{8}$$

The above capacity model is an exponential regression model developed on the basis of a gap-acceptance theory (*8*). Unlike in HCM 2000, the critical headways were assumed to be different for different roundabout geometry classified in regard to the numbers of circulating lanes and entry lanes. In this model, shorter critical headways were used for a two-lane roundabout than for a one-lane roundabout.

The capacity models were also derived by using an M2 distribution (Equation 9) and an M3 distribution (Equations 10 and 11) as follows (*9–11*):

$$C_e = \frac{3{,}600 \cdot q_c \cdot \left(1 - \Delta \cdot q_c\right) \cdot e^{-q_c\left(t_c - \Delta\right)}}{1 - e^{-q_c t_f}} \tag{9}$$

$$C_e = \frac{3{,}600 \cdot q_c \cdot \alpha \cdot e^{-\lambda\left(t_c - \Delta\right)}}{1 - e^{-\lambda t_f}} \tag{10}$$

where α is determined from Equation 5.

$$C_e = \frac{3{,}600 \cdot \left(1 - \Delta \cdot q_c + 0.5 \cdot \alpha \cdot q_c \cdot t_f\right) \cdot e^{-\lambda\left(t_c - \Delta\right)}}{t_f} \tag{11}$$

where α is determined from Equation 6.

Tanyel et al. tested the M1, M2, and M3 capacity models and found that the M3 model performed best for the six roundabouts they studied in Turkey (*12*). However, it was found that the M1 model performed best for the roundabouts in the United States (*1*).

Consideration of Trucks

Some studies have considered the effects of trucks on roundabout capacity. The HCM 2000 and HCM 2010 methods (*1, 8*) convert the number of vehicles into passenger car unit (pcu) by using the heavy vehicle factor as follows:

$$f_{\mathrm{HV}} = \frac{1}{1 + \left(e_{\mathrm{HV}} - 1\right) p_{\mathrm{HV}}} \tag{12}$$

where e_{HV} is the passenger car equivalent of a heavy vehicle (pcu/HV) (default value is 2.0), and p_{HV} is the proportion of heavy vehicles in the traffic stream. The flow in vehicles/h (veh/h) is divided by f_{HV} to calculate the flow in pcu/h. Because of a higher pcu for trucks, higher truck volume in the entry lane increases the entry flow (in pcu/h) and consequently reduces the entry capacity. This reduction will indirectly reflect a truck's longer critical headway and follow-up time. However, the reduction in the capacity may not be proportional to the increase in truck volume in the entry flow. In other words, the ratio of the truck's critical headway (or follow-up time) to the car's critical headway (or follow-up time) may not be equivalent to the truck's pcu. Thus, there is a lack of consideration of the difference in driver gap-acceptance behavior between cars and trucks.

In this regard, an Australian report suggested that the critical headway and the follow-up time are different for heavy vehicles and cars (*2*). The report suggested that factors be included to take into account this difference as follows:

$$\left(t_c\right)_{\mathrm{HV}} = f_{\mathrm{GA}}\left(t_c\right)_C, \left(t_f\right)_{\mathrm{HV}} = f_{\mathrm{GA}}\left(t_f\right)_C \tag{13}$$

where $(t_c)_{\mathrm{HV}}$ and $(t_c)_C$ are the critical headways for heavy vehicles and cars (s), respectively; $(t_f)_{\mathrm{HV}}$ and $(t_f)_C$ are the follow-up times for heavy vehicles and cars (s), respectively; and f_{GA} is the gap-acceptance parameter factor. The factor f_{GA} is greater than or equal to 1 to reflect longer critical headway and follow-up time for heavy vehicles than for cars. However, the study found that there was no need to adjust gap-acceptance parameters for heavy vehicles (i.e., $f_{GA} = 1$) on the basis of the field data for one traffic circle. The study also suggested that the critical headway is longer when the driver enters in front of heavy vehicles rather than cars. However, Zheng et al. observed that the critical headway for heavy vehicles is longer than for cars and motorcycles (*13*).

As in this study, Akçelik & Associates Pty Ltd. suggested adjusting the critical headway and the follow-up time for the entire entry flow by using the heavy vehicle factor as follows (*14*):

$$t_c' = \frac{t_c}{f_{\text{HV}}} \qquad t_f' = \frac{t_f}{f_{\text{HV}}} \tag{14}$$

where t_c' and t_f' are the critical headway and the follow-up time adjusted for heavy vehicle effects in the entry flow, respectively.

However, there is a need to investigate the validity of the same adjustment factor for critical headway and follow-up time. Although some studies [e.g., Troutbeck (*2*)] reported the effect of the gap-acceptance parameters adjusted for heavy vehicles on the reduced capacity, they have not investigated this effect by using extensive field data. Thus, further studies are needed to examine the effect of trucks on driver gap-acceptance behavior and incorporate such effect into the estimation of roundabout capacity.

METHOD

To reflect the effect of trucks on the capacity, gap-acceptance parameters are determined for cars and trucks separately. Then the representative gap-acceptance parameters for the entire entry flow are calculated as a volume-weighted average of the parameters for cars and trucks. If the entry flow consists of cars and trucks only, the critical headway and the follow-up time are calculated with the following equations:

$$t_c' = t_{c,\text{car}} \cdot (1 - p_{\text{truck}}) + t_{c,\text{truck}} \cdot p_{\text{truck}} \tag{15}$$

$$t_f' = t_{f,cc} \cdot (1 - p_{\text{truck}})^2 + (t_{f,ct} + t_{f,tc}) \cdot (1 - p_{\text{truck}}) \cdot p_{\text{truck}} + t_{f,tt} \cdot p_{\text{truck}}^2 \tag{16}$$

where

t_c' = adjusted critical headway (s);
p_{truck} = proportion of trucks;
$t_{c,\text{car}}$ and $t_{c,\text{truck}}$ = critical headways for cars and trucks, respectively (s);
t_f' = adjusted follow-up time (s); and
$t_{f,cc}$, $t_{f,ct}$, $t_{f,tc}$, $t_{f,tt}$ = follow-up times for a car following a car (car/car), a truck following a car (car/truck), a car following a truck (truck/car), and a truck following a truck (truck/truck), respectively (s).

The follow-up times for each vehicle-following case were weighted on the basis of the probability of a lead-vehicle and following-vehicle combination. These adjusted gap-acceptance parameters (t_c', t_f') were used to estimate the capacity with Equations 7 through 11.

DATA

To observe car and truck movements at roundabouts, video footage and geometric drawings for 11 roundabouts in Vermont, Wisconsin, and Ontario, Canada, were obtained. The locations, dates of video footage, and traffic volumes at all entry legs are shown in Table 1. Some roundabouts were chosen because truck volumes were high. Dimensions of road geometry for each roundabout were manually measured by the authors by using the scaled drawings described in Table 2. Sample screenshots of video footage and geometric drawings of three roundabouts (where queued entry vehicles were observed) are shown in Figure 1. All roundabouts have two full circulatory lanes or one partially circulatory lane except for the roundabouts in Brattleboro, Vermont, and at Thompson South in Madison, Wisconsin, which have one circulatory lane only. Although the width of the circulatory lane at the Brattleboro and Thompson South roundabouts is wide enough for two lanes, there is no lane marking.

Gap acceptance and rejection, the follow-up time, and free-flow speed were collected from the video for the above 11 sites. Unusual driver behavior, such as gap-forcing behavior and violation of the right-of-way, and unnecessarily tentative drivers were noted. All the data were collected for cars and trucks separately.

Gap data include the time of entry, time gap (s), vehicle type (car or truck), and gap condition (accepted or rejected) at all entry legs visible from the video. Gaps were measured by taking the difference in times when two consecutive circulating vehicles passed the conflict point for a given entry leg. Because there was not much difference in the distributions of accepted and rejected gaps among

TABLE 1 Studied Roundabouts: Location, Date of Video Footage, and Traffic Volume at All Entry Legs

Roundabout	Intersecting Roads	City and State or Province	Date of Video Footage	Traffic Volume (veh/h)
Brattleboro	VT-9 & US-5	Brattleboro, Vt.	July 16, 2003	2,052
Waterloo	Arthur Street & Sawmill Road	Waterloo, Ontario	Jan. 13, 2011	1,800
32 & 57	STH-57 & STH-32 (Broadway Street)	DePere, Wis.	May 19, 2010	3,864
78 & 92	STH-78, STH-92, 8th Street, & CTH ID (Mount Horeb)	Madison, Wis.	April 8, 2010	828
42 & 43	STH-42 & I-43 northbound off ramp (east)	Sheboygan, Wis.	April 22, 2010	1,308
Vanguard	STH-42 & Vanguard Avenue	Sheboygan, Wis.	April 23, 2010	1,188
Bennett	STH-18 & Bennett Road	Dodgeville, Wis.	March 30, 2010	912
Moorland North	Moorland Road & I-43 (north)	New Berlin, Wis.	May 5, 2010	2,988
Moorland South	Moorland Road & I-43 (south)	New Berlin, Wis.	May 12, 2010	1,152
Thompson North	Thompson Drive & STH-30 eastbound off-ramp	Madison, Wis.	April 29, 2010	1,308
Thompson South	Thompson Drive & Commercial Avenue	Madison, Wis.	April 13, 2010	960

TABLE 2 Studied Roundabouts: Geometric Factors

Roundabout	No. of Legs	Inscribed Circle Diameter (m)	Central Island Diameter (m)	Truck Apron (m)	Entry Width (m)	Exit Width (m)	Circulatory Roadway Width (m)	Splitter Island Width (m)	Entry Angle (°)
Brattleboro	4	56.0	32.4	2.4	9.7	9.7	12.2	5.0	30.0
Waterloo	4	60.0	40.0	3.3	8.3	8.3	10.0	10.8	17.8
32 & 57	4	53.3	22.9	3.8	9.1	9.1	11.4	9.0	23.8
78 & 92	4	38.6	13.7	4.3	6.9	7.7	9.4	4.9	27.0
42 & 43	4[a]	47.6	22.9	3.8	8.4	8.4	9.9	8.4	27.5
Vanguard	4	61.0	25.9	4.6	7.6	9.1	9.1	12.4	20.6
Bennett	4	57.0	29.0	3.8	9.9	8.4	10.7	13.9	24.4
Moorland North	4[b]	50.0	31.2	1.9	6.7	6.7	7.2	10.3	27.5
Moorland South	4[c]	37.0	19.2	1.9	5.8	5.3	6.3	8.8	21.9
Thompson North	4	50.7	29.0	0.8	7.6	9.1	10.7	8.4	23.8
Thompson South	3[c]	42.0	22.9	0.8	7.6	9.1	9.1	6.9	25.0

NOTE: No. = number.
[a]There is no exit at one leg and no entrance at another leg.
[b]There is no exit at one leg and no entrance at another leg. There are also multiple bypass lanes.
[c]There is no exit at one leg.

different entry legs, all gaps were combined for each roundabout. A total of 35 h of video footage was viewed, and 2,790 gap data points were collected from the 11 roundabouts. A minimum value of all of the time-gap data for each roundabout was taken as the minimum headway.

The follow-up time data include the time of entry, the follow-up times (s), and the types of lead and following vehicles (car–car, car–truck, truck–car, or truck–truck). The follow-up times were measured by taking the difference in times when two consecutive queued entering vehicles passed the entry point by using the same gap between the circulating vehicles for a given entry leg. Queued vehicles are defined as the vehicles that completely stopped in a queue at the entry leg before they entered the roundabout. If there are multiple entry lanes, the follow-up times were measured in the lane(s) where the entering vehicles have conflict with the circulating vehicles. A total of 23 h of video footage was viewed and 275 follow-up time data points were collected from nine roundabouts. The size of sample follow-up times was insufficient for the Thompson North and Thompson South roundabouts in Madison because of a lack of queued vehicles at the entry legs.

The circulating flow data were also collected for all lanes of the circulatory roadway. In the case of two-lane roundabouts, the distributions of headways in both lanes are assumed to be the same, and the sum of flows in two lanes was used as one circulating flow (*15, 16*). Free-flow speeds for all major turning routes for cars and trucks in a circulatory roadway were also collected. Distances of movement paths were measured by using the geometric drawings, and free-flow travel times to traverse the path were recorded from the video. Free-flow speed was calculated as the distance of the path divided by the free-flow travel time. Free-flow speeds of cars and trucks were used to evaluate whether trucks obstructed the circulating flow because of their lower speed. Free-flow speed was also used to consider the effect of the exiting vehicles on gaps. The measured gap sometimes misrepresents the actual gap perceived by the driver of the entering vehicles when the circulating vehicles exit (*17*). To account for this effect, the time at which the exiting vehicles would have reached the conflict point (if they continued traveling the circulatory roadway) can be estimated by using the free-flow speed and the distance between the exit point and the conflict point. Eight hours of video footage were viewed, and 482 data points were collected for free-flow speed from the 11 roundabouts.

Finally, field capacity was observed at the roundabouts in Brattleboro; Waterloo, Ontario; and DePere, Wisconsin (32 & 57) because queued entering vehicles and saturated entry flows occurred only at these sites. The number of the entering vehicles at a given entry leg was recorded from the time at which the first vehicle in a queue entered the roundabout to the time the queue was cleared in every 1-min interval. During the same time period, the number of circulating vehicles that had conflicts with the entering vehicles from the given leg was also recorded. Seventy-eight pairs of entry and circulating flows were taken at these three sites.

RESULTS AND DISCUSSION

Critical Headway and Follow-up Time

In the measurement of the time gaps from the video, it was found that 14% of gaps were affected by the exiting vehicles. For these gaps, the time at which the exiting vehicles would have reached the conflict point if they had not exited was used to estimate the perceived gap. These estimated gaps were shorter than the gaps measured without considering the exiting vehicles.

It was also observed that some vehicles, particularly trucks, aggressively entered the roundabout even when a sufficient gap was not available and forced the circulating vehicles to yield to the entering vehicle. This type of gap-forcing behavior obstructed the circulating flow. Detailed discussion on the obstruction of the circulating flow at the Brattleboro roundabout is described in Dahl and Lee (*18*). The higher likelihood of trucks' gap-forcing behavior was observed at all other roundabouts. The gaps created by the entering vehicle's gap-forcing behavior were not used for the estimation of the critical headway because the gaps do not represent actual available gaps that provide the opportunity of entry.

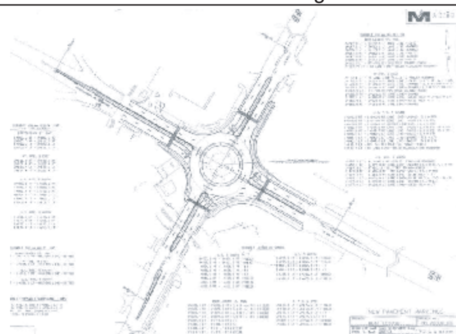
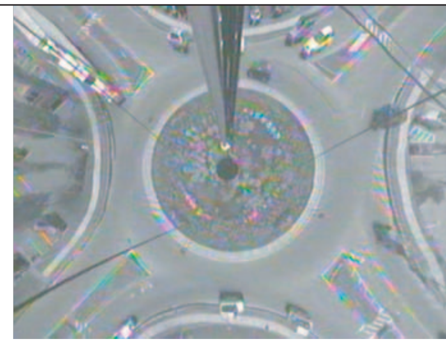
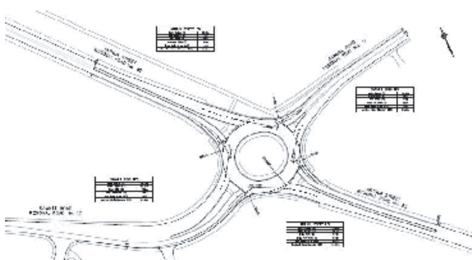
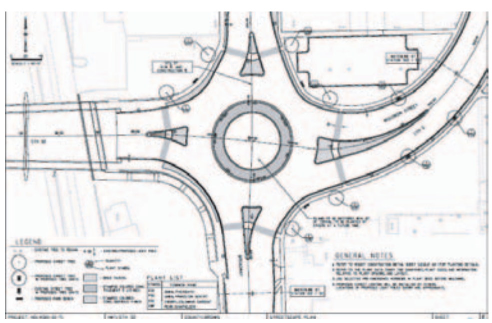
Roundabout	Geometric drawing	Video screenshot
Brattleboro See notes below images for road names	 Top Left – Brattleboro State Highway (to I-91) Bottom Left – US Route 5 Bottom Right – Vermont Route 9 Top Right – US Route 5	 Bottom Left – Brattleboro State Highway Bottom Right – US Route 5 Top Right – Vermont Route 9 Top Left – US Route 5
Waterloo	 Top Left & Bottom Right – Arthur Street Bottom Left & Top Right – Sawmill Road	 Top Left & Bottom Right – Arthur Street Bottom Left & Top Right – Sawmill Road
32 & 57	 Top – Broadway/State Highway 57 Left – State Highway 32 Bottom – Broadway Avenue Right – Wisconsin Street	 Top Right – Broadway/State Highway 57 Top Left – State Highway 32 Bottom Left – Broadway Avenue Bottom Right – Wisconsin Street

FIGURE 1 Geometric drawings and screenshots of video footage for Brattleboro, Waterloo, and 32 & 57 roundabouts.

The critical headways were estimated by using these gap data. Two methods were used to estimate the critical headway: (*a*) the Raff method (*19*) and (*b*) the probability equilibrium method (*20*). The Raff method defines the critical headway as the size of the gap that is equally likely to be accepted or rejected (*21*). This method determines the critical headway by using cumulative values of individual entry vehicles' accepted and rejected gaps. The critical headway was determined at the point of intersection between the two cumulative curves of the accepted gaps and rejected gaps plotted on the same graph.

The probability equilibrium method assumes that the probability distribution function (PDF) of the critical headway is described as follows (*20*):

$$F_{tc}(t) = \frac{F_a(t)}{F_a(t) + 1 - F_r(t)} \quad (17)$$

TABLE 3 Summary of Data: Critical Headway

Roundabout	Sample Size	Graphical $t_{c,cars}$ (s)	Graphical $t_{c,trucks}$ (s)	Probability Equilibrium $t_{c,cars}$ (s)	Probability Equilibrium $t_{c,trucks}$ (s)	Average $t_{c,cars}$ (s)	Average $t_{c,trucks}$ (s)	Minimum Headway (s)
Brattleboro	528	3.8	5.2	3.9	5.3	3.9	5.3	0.3
Waterloo	217	4.0	6.0	4.2	5.3	4.1	5.7	0.9
32 & 57	285	3.2	4.2	3.7	4.7	3.5	4.5	0.3
78 & 92	350	5.0	—[a]	5.4	—[a]	5.2	—[a]	0.5
42 & 43	250	3.8	5.0	4.0	6.0	3.9	5.5	0.5
Vanguard	227	4.1	4.5	4.0	4.6	4.1	4.6	0.3
Bennett	156	4.4	6.6	5.1	5.6	4.8	6.1	0.4
Moorland North	291	4.1	4.5	4.5	5.6	4.3	5.1	0.3
Moorland South	273	4.1	4.5	4.5	4.7	4.3	4.6	0.5
Thompson North	143	3.9	—[a]	4.4	—[a]	4.2	—[a]	0.5
Thompson South	149	4.2	—[a]	4.9	—[a]	4.6	—[a]	0.8

NOTE: — = not available.
[a]Due to lack of entering trucks, the critical headways could not be estimated.

where

$F_{tc}(t)$ = PDF of critical headway,
$F_a(t)$ = PDF of an accepted gap t, and
$F_r(t)$ = PDF of a maximum rejected gap t.

If a time gap t is sorted in an ascending order, $j = 1, 2, \ldots, N$, the critical headway is calculated with the following expression:

$$t_c = \sum_{j}^{N} \left[p_{tc}(t_j) \cdot (t_j + t_{j-1})/2 \right] \tag{18}$$

where $p_{tc}(t_j)$ is the frequencies of the estimated critical headways between j and $j - 1$. This method does not require assumptions of data distribution and accounts for all relevant rejected gaps, not only the maximum rejected gaps.

The critical headways for all roundabouts are shown in Table 3. Generally, the critical headways estimated by using the graphical and probability equilibrium methods were similar. An average of the two critical headways was used as a representative critical headway for each roundabout. In all roundabouts, the critical headway for trucks was longer than that for cars. The reason is that trucks require longer headway to enter the roundabout because of their larger size and slower acceleration.

The follow-up times for different vehicle-following conditions are shown in Table 4. It was found that the follow-up time was longer when a truck was a lead vehicle, a following vehicle, or both. The follow-up time for the truck–car case was longer than the follow-up

TABLE 4 Summary of Data: Follow-Up Time and Free-Flow Speed

Roundabout	Follow-Up Time: Sample Size	$t_{f,cc}$ (s)	$t_{f,ct}$ (s)	$t_{f,tc}$ (s)	$t_{f,tt}$ (s)	Free-Flow Speed: Sample Size	Car Speed (km/h)	Truck Speed (km/h)	% Speed Difference[a]
Brattleboro	76	2.1	4.2	5.3	8.5	124	29	20	30.1
Waterloo	34	2.3	5.0	6.8	7.4	31	39	30	22.8
32 & 57	31	2.1	3.3	5.3	—[c]	44	31	24	21.9
78 & 92	37	1.6	2.6	—[c]	—[c]	26	33	23	30.8
42 & 43	22	2.3	2.8	5.5	7.8	30	33	25	24.3
Vanguard	16	2.2	2.7	5.4	—[c]	44	33	25	24.4
Bennett	15	2.2	3.5	5.5	5.7	36	37	29	22.5
Moorland North	24	2.3	3.1	4.5	—[c]	33	22	17	19.1
Moorland South	20	2.0	3.5	5.2	—[c]	34	22	19	14.3
Thompson North	—[b]	—[c]	—[c]	—[c]	—[c]	32	39	29	25.1
Thompson South	—[b]	—[c]	—[c]	—[c]	—[c]	28	37	29	19.4

NOTE: — = not available.
[a]% speed difference = (car speed − truck speed)/car speed * 100.
[b]No queued entering vehicle was observed.
[c]Due to lack of queued entering vehicles, follow-up times could not be estimated.

time for the car–truck case because it took a longer time for the lead truck to enter the roundabout than for the lead car. Although a truck could rarely follow another truck by using the same gap at the entry leg of most roundabouts, it was found that the follow-up time for the truck–truck case was the longest because of the lead truck's slow entry and the following truck's low acceleration.

Free-Flow Speed

Free-flow speeds for cars and trucks are shown in Table 4. For all roundabouts, cars traveled at a higher free-flow speed than did trucks. The reason is that trucks require a larger turning radius and they tend to travel slower along the curved path of a circulatory roadway. The truck's slower free-flow speed compared with the car's free-flow speed indicates that trucks are more likely to obstruct the circulating flow. This tendency to obstruct indicates that trucks tend to decrease the circulating flow and increase the likelihood of available gaps for the entering vehicles.

Correlation with Geometric Factors

To evaluate the effect of road geometry on driver gap-acceptance behavior, the critical headways and the follow-up times were related to eight geometric factors shown in Tables 3 and 4 by using a linear regression. The correlation among the geometric factors was checked to avoid a multicollinearity problem. The correlation analysis shows that some factors were highly correlated (e.g., the inscribed circle diameter and the central island diameter).

It was found that relationships between the critical headway and all geometric factors were not statistically significant at a 95% confidence level. However, relationships between the follow-up time and some geometric factors were statistically significant. For instance, the relationship between the follow-up time and the central island diameter was significant for the car–car and car–truck cases at a 95% confidence level. Figure 2 shows that as the central island diameter increases, the follow-up time increases. This contradicts the findings of the Australian study that the follow-up time decreases with the inscribed circle diameter because it is easier to enter a larger roundabout (*8*). However, it also takes longer for the driver to perceive how to navigate the roundabout (e.g., check which lane he or she should enter) (*22*). It appears that the latter effect was more dominant in the studied roundabouts. Thus, trucks tend to follow cars more slowly at a larger roundabout.

Given that sample size for these linear regression models was low (eight to 11 data points), some relationships that were significant at a 90% confidence level were also examined. As shown in Figure 2, a car's follow-up time decreases when it follows trucks as the entry angle increases. This decrease also contradicts the findings of the UK study that the capacity decreases (this indirectly reflects that the follow-up time increases) as the entry angle increases as a result of more difficulty with turning (*23*). However, when it takes longer for trucks to negotiate a sharper curve to enter the roundabout, cars tend to maintain shorter headways with trucks. The reason is potentially that car drivers wish to enter the roundabout by following trucks more closely as a truck's entry is delayed. Finally, the car–car follow-up time increases as the width of the splitter island increases. This increase shows that the splitter island significantly affects only the car–car follow-up time.

Comparison of Capacity Models

The capacities of the three roundabouts were estimated by using the adjusted gap-acceptance parameters (Equations 15 and 16) and the existing capacity models. The percentage of trucks in each roundabout was calculated on the basis of the car and truck counts in entry legs. The percentages for the Brattleboro, Waterloo, and DePere (32 & 57) roundabouts were 11%, 19%, and 5%, respectively. Because the term $t_{f,tt}$ could not be determined for the DePere (32 & 57) roundabout as a result of the lack of data, it was assumed to be equal to $t_{f,tc}$. Minimum headways of the circulating flow (Δ) for the Brattleboro, Waterloo, and DePere (32 & 57) roundabouts were 0.3 s, 0.9 s, and 0.3 s, respectively.

The capacity was also estimated by using SIDRA INTERSECTION 5.1, which accounts for the effects of geometry on gap-acceptance parameters and the capacity (*14*). The Australian capacity model was used because the capacity estimated by the model is more sensitive to roundabout geometry than the HCM model. The effect of heavy vehicles was considered for all percentages of heavy vehicles. However, it took a significant amount of time to obtain approach-based entry flow data for cars and trucks separately (the required inputs for SIDRA) from the video. Thus, the capacity was estimated for the Brattleboro roundabout by using only SIDRA. The default value of the heavy vehicle factor (= 2.0) was used to consider the effect of trucks. The capacities were estimated for different circulating flows by using the capacity models (Equations 7–11) and compared with the observed capacity as shown in Figure 3.

It was found that the observed capacity was lower for the roundabout with a higher truck percentage. The reason is that vehicles are more likely to wait for longer gaps (i.e., longer critical headway) and it takes longer for two vehicles to enter the roundabout by using the same gap (i.e., longer follow-up time). The observed capacity was less sensitive to the circulating flow at the Brattleboro and Waterloo roundabouts, which have relatively higher truck percentages than the DePere (32 & 57) roundabout. This finding reflects that the rate of reduction in the number of entering vehicles with an increase in the circulating flow is lower when there are more trucks. This finding is intuitive in the sense that as the available gaps approach the minimum acceptable gaps for trucks as a result of higher circulating flow, it becomes more difficult for trucks to enter the roundabout than for cars. When gaps are shorter than the minimum acceptable gaps for trucks (but longer than the minimum acceptable gaps for cars), the number of entering trucks is less likely to be affected by the circulating flow than the number of entering cars. Thus, when more trucks present at the roundabout, the capacity will not greatly change.

Most capacity models closely reflected that trend, as shown in Figure 3. In particular, Troutbeck's model reflected the high sensitivity of the capacity to the circulating flow at the DePere (32 & 57) roundabout more accurately than the other models. The capacity estimated by using SIDRA was slightly higher than the capacities estimated by the other models for the Brattleboro roundabout. The reason is that the larger width of a single circulating lane at the roundabout had to be coded as the width of two circulating lanes. The capacity models derived from the M3 distribution (Troutbeck's and Akçelik's models) generally provided a good fit to the observed capacities for all three roundabouts. However, the accuracy of estimation depends mainly on the proportion of free vehicles (α) described in a function of the circulating flow. For instance, Akçelik's function showed lower error for the roundabouts with a higher truck percentage, and Troutbeck's function showed lower error for the roundabout with a lower truck percentage.

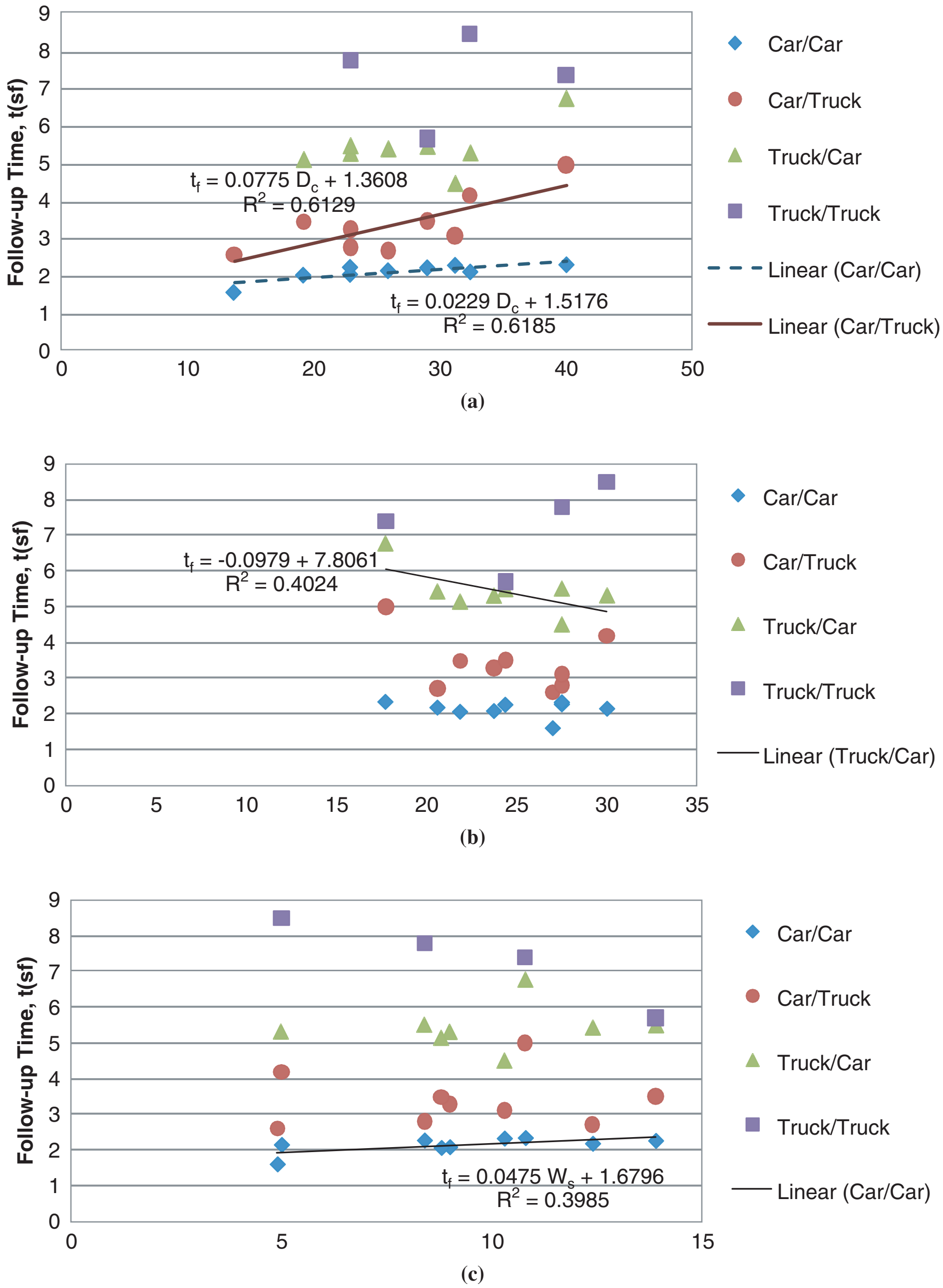
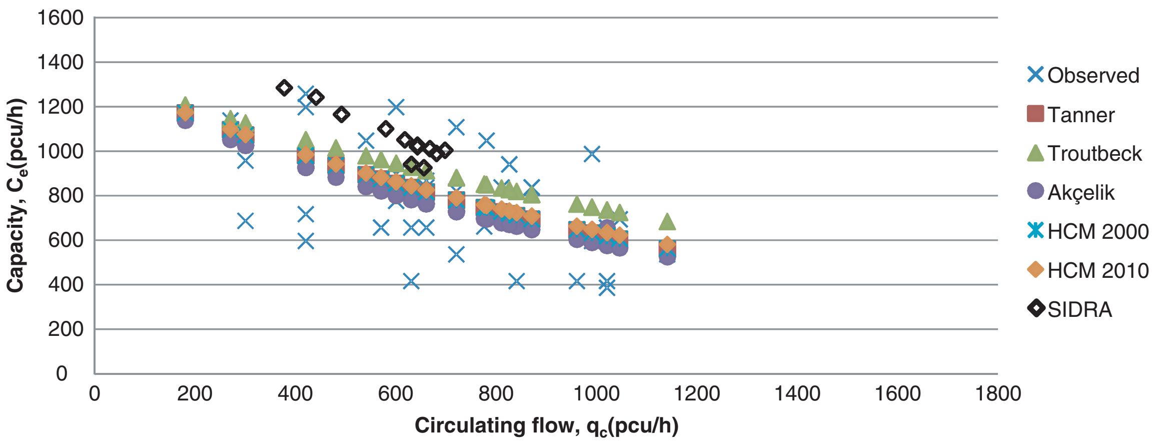


FIGURE 2 Relationships between follow-up time and geometric factors: (*a*) central island diameter, D_c (m); (*b*) entry angle (degrees); and (*c*) splitter island width, W_s (m).

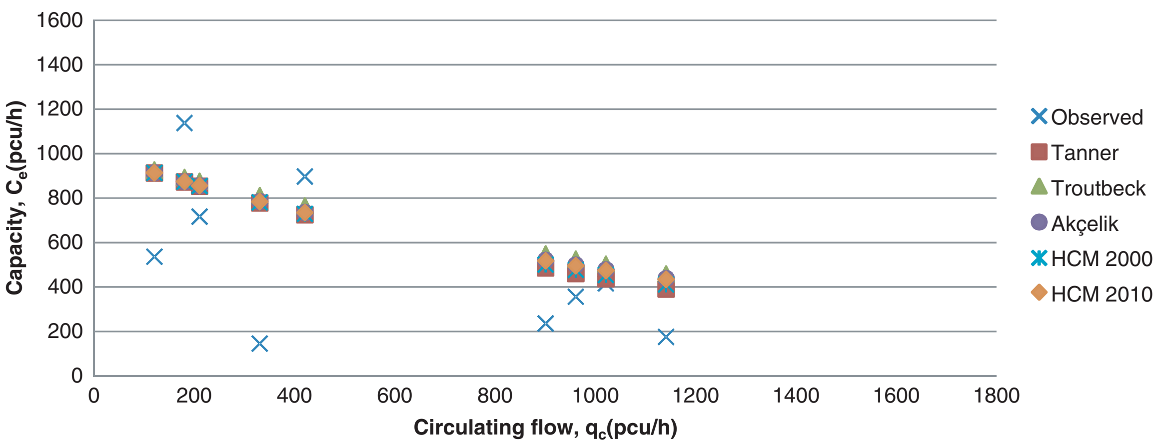
To evaluate the effectiveness of the adjusted gap-acceptance parameters, the capacities estimated by using the adjusted and unadjusted parameters were compared. Because cars are dominant in the entry flow, if the difference in gap-acceptance behavior between cars and trucks is not considered, the gap-acceptance parameters will be similar to the parameters for cars only. Thus, the unadjusted gap-acceptance parameters denote the critical headway for cars and the follow-up time for a car following a car assuming a zero truck percentage. As shown in Figure 4, the root mean square errors (RMSEs) of the estimated capacity were lower for the adjusted parameters than for the unadjusted parameters. It was also found that the percentage reduction in RMSE was greater for the roundabout with a higher truck percentage. This finding indicates that gap-acceptance parameters need to be adjusted for trucks to estimate the capacity for the roundabouts more accurately, and the accuracy is more likely to be improved for the roundabouts with a higher truck percentage.

Effect of Truck Percentage on Capacity

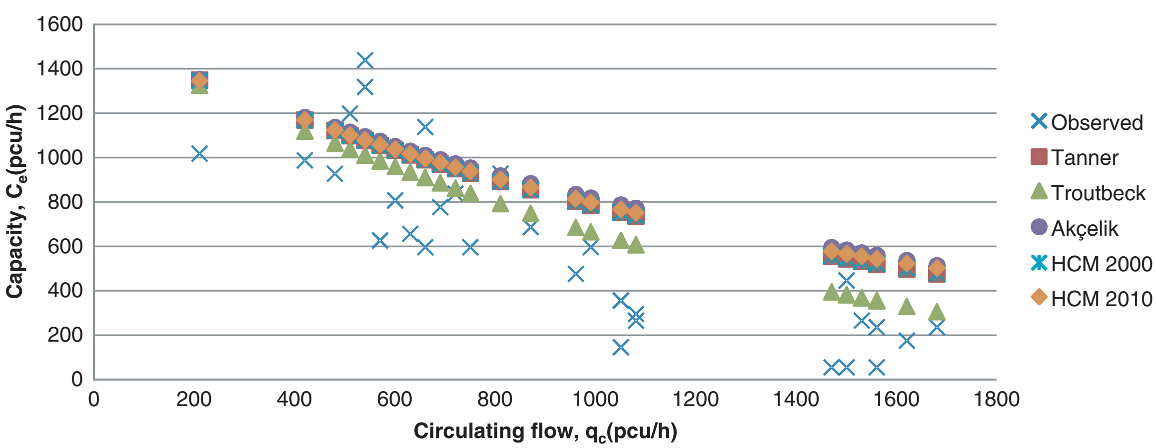
For demonstration purposes, Troutbeck's model was applied to the Waterloo and DePere (32 & 57) roundabouts to understand the more general trend of the capacity affected by truck percentage. Capacities were estimated with five hypothetical truck percentages (0%, 5%,



(a)



(b)



(c)

FIGURE 3 Comparison of results for three roundabouts: estimated capacities with adjusted gap-acceptance parameters for trucks for (*a*) Brattleboro, (*b*) Waterloo, and (*c*) 32 & 57 roundabouts.

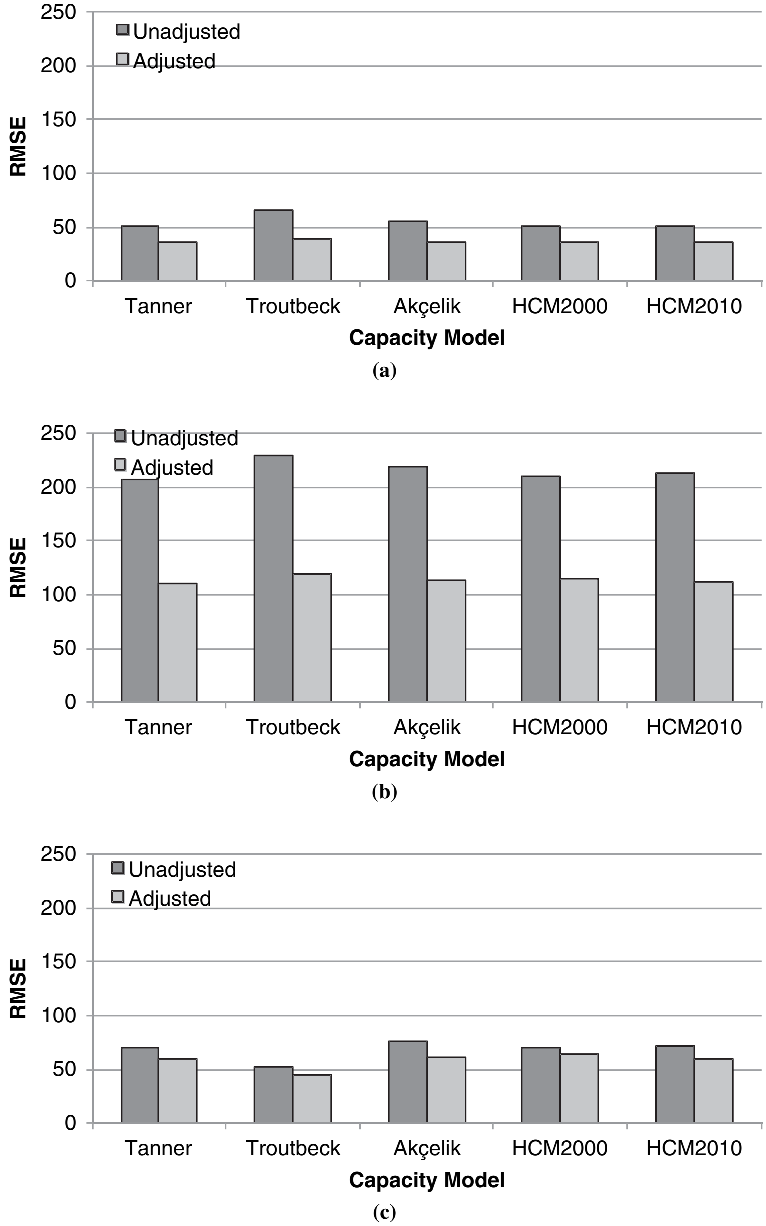


FIGURE 4 Comparison of results for three roundabouts, estimation errors for (*a*) Brattleboro, (*b*) Waterloo, and (*c*) 32 & 57 roundabouts.

10%, 15%, and 20%) and the circulating flow in the range of 0 to 1,800 pcu/h as shown in Figure 5*a.*

It was assumed that the critical headways for cars and trucks and the follow-up times for all vehicle-following cases are not affected by a change in truck percentage. Thus, only the adjusted critical headways and follow-up times change as truck percentage changes.

The results showed that the capacity decreases as truck percentage increases, but the amount of capacity reduction is less at higher circulating flow. The results also show that the rate of capacity reduction with an increase in the circulating flow is lower at a higher truck percentage.

This effect is more noticeable at the Waterloo roundabout, which has a longer adjusted critical gap and follow-up time than the DePere (32 & 57) roundabout as shown in Figure 5*b*. This finding indicates that change in the circulating flow is less likely to affect the capacity as truck percentage increases when the adjusted gap-acceptance parameters are higher.

CONCLUSIONS AND RECOMMENDATIONS

As a growing number of roundabouts are built in areas with high truck volume, a more accurate method of estimating the entry capacity is needed. In that regard, this study proposes the method of adjusting gap-acceptance parameters for trucks considering a truck's slower speed and larger radius required for turning. The study assumes that the ratio of truck–car critical headway is not always equal to the ratio of truck–car follow-up time, unlike in previous studies. Also,

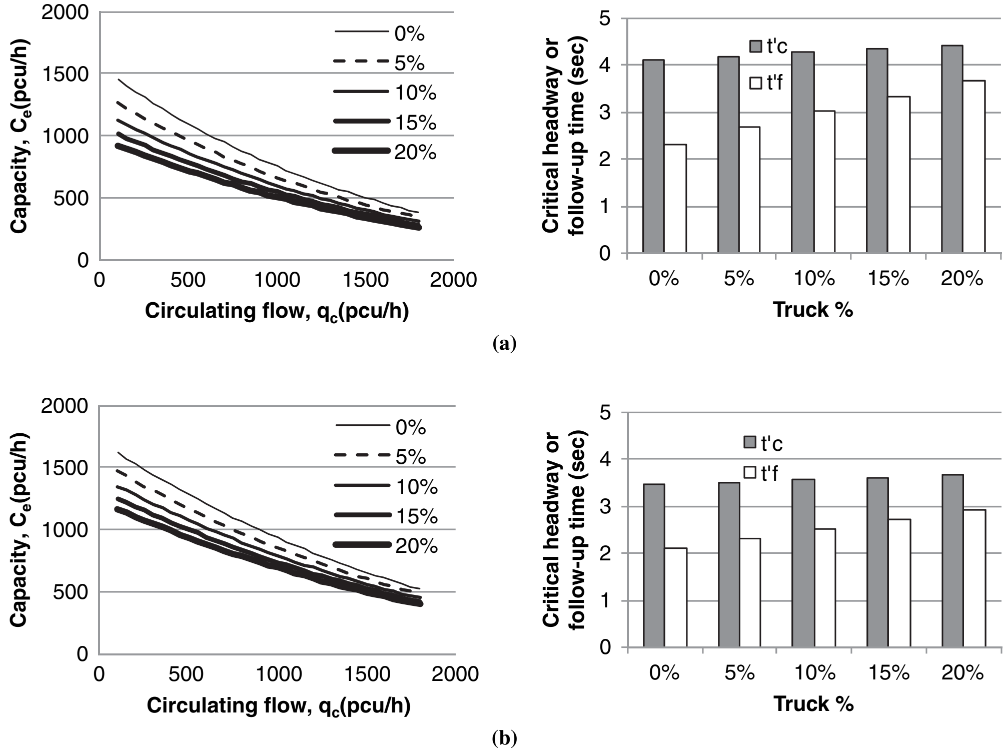


FIGURE 5 Change in capacity and adjusted gap-acceptance parameters with change in truck percentage for (*a*) Waterloo and (*b*) 32 & 57 roundabouts.

the follow-up time was assumed to be different for different vehicle-following cases. Vehicle movements were observed at 11 roundabouts in Vermont, Wisconsin, and Ontario, and the critical gap and the follow-up time were estimated for cars and trucks separately. The capacity was estimated by using various capacity models with the adjusted gap-acceptance parameters and compared with actual capacity observed from the field. The findings of the study are summarized as follows:

1. The critical headways were longer for trucks than for cars. The follow-up times were longer in the order of a truck following a truck, a car following a truck, a truck following a car, and a car following a car.
2. A truck's free-flow speed was lower than a car's free-flow speed in a circulatory roadway. Thus, a truck's entry caused obstruction of the circulating flow and increased the likelihood of acceptable gaps for entering vehicles.
3. Follow-up times for some truck-involved vehicle-following cases were associated with roundabout geometric factors. The follow-up time for trucks following cars increases as the central island diameter increases, whereas the follow-up time for cars following trucks increases as the entry angle decreases.
4. The rate of reduction in the observed capacity with an increase in the circulating flow is lower at the roundabout with a higher truck percentage. It was found that even small percentages of truck traffic had an immediate effect on roundabout operation.
5. The estimation errors of the capacity were lower for the capacity models with the adjusted gap-acceptance parameter than for the models with the unadjusted gap-acceptance parameters. This indicates that the adjusted gap-acceptance parameters improve the accuracy of capacity estimation particularly for the roundabouts with high truck volume.
6. As truck percentage increased, the critical headway and the follow-up time for the roundabout increased, with resulting lower capacities.

On the basis of the findings, it is recommended that gap-acceptance data be collected for cars and trucks separately and that critical gaps and follow-up times also be estimated separately. Then the gaps and times are to be adjusted to volume-weighted averages. These adjusted gap-acceptance parameters can be used as inputs to various gap-acceptance capacity estimation models to estimate the capacity. Consequently, relationships between the capacity and the circulating flow need to be determined for different truck percentages to estimate the capacity more accurately. Also, roundabout geometric factors need to be modified such that they can reduce the entry time for trucks and ultimately increase the capacity.

There are some limitations in this study. Because of a lack of trucks in the entry flow, the gap-acceptance parameters for trucks could not be determined for some roundabouts. Also, it was assumed that individual drivers' minimum headway and gap-acceptance behaviors were independent from truck percentage change of the entire entry flow and the circulating flow. However, if the behaviors and percentages are correlated, the adjusted gap-acceptance parameters may provide the biased result. For instance, if the truck percentage is high and the entering vehicles are required to wait longer, they are more likely to accept shorter gaps (*6*). Finally, the gap acceptance depends only on available gaps in the circulating flow. However, it is possible that gap acceptance is also affected by drivers' sight and the aggressiveness of their driving, as well as road surface conditions.

In future studies, more data need to be collected from roundabouts with a wide range of truck percentages to understand better the general effect of truck percentage on the capacity. Observing the ways in which individual car drivers and truck drivers behave differently at roundabouts under various geometric, traffic, and weather conditions is also recommended.

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