

A Roundabout Capacity Survey Method Using Gap Acceptance Cycles and Vehicle Trajectory Data

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Rahmi Akçelik

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REVIEW

Mark Besley (Director, Akcelik & Associates Pty Ltd, t/a SIDRA SOLUTIONS) carried out a quality review of this report.

DISCLAIMER

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ABSTRACT

The objective of this report is to describe a new gap acceptance capacity survey method using vehicle trajectory data. Although the survey method was developed by application to a single-lane roundabout, it can also be used for multi-lane roundabouts and other gap acceptance situations including unsignalised (stop and give-way / yield controlled) intersections, and permitted turns, turn on red and unsignalised slip / bypass lanes at signalised intersections, and various merge situations. The survey uses gap acceptance cycles based on a traffic signal analogy approach used for gap acceptance capacity and performance model development. Real-world vehicle trajectory data were collected at a single-lane roundabout with moderate volume conditions in Raleigh, NC, USA. The survey method defines reliable gap acceptance cycles for measuring follow-up headway, critical headway and capacity cycle-by-cycle simultaneously. This is done by observing the departure of queued vehicles in saturated unblocked periods when all entry vehicles are queued. The results compared well against values obtained from some established methods. Average blocked time, unblocked time and gap acceptance cycle time estimates were assessed using M3D, M3DS, M3B, M3T, M1 and M2 arrival headway distribution models with observed follow-up and critical headway values. Gap acceptance capacity estimates were assessed for these models as well as the HCM default model and the general Siegloch M1 model used in the US HCM. The results confirmed the validity of the survey method, supporting the novel signal analogy concept with observations of real-world data. The assessments comparing the performance of different gap acceptance capacity models were not conclusive as they were limited by the small size of the dataset available from this survey. The capacity models with low levels of bunching in circulating flows performed better for this survey. Improvements in the performance of the calibrated M3D and M3DS models confirmed the low levels of bunching in circulating flows. It is also shown that the survey method can be used for determining gap acceptance factors for different vehicle classes in entry lanes. Future research is recommended on assessing the various bunching models for opposing stream headway distributions, and the implementation of the new survey method including comparison of capacity models to gap acceptance situations for different traffic facilities.

Keywords: Intersection, Roundabout, Capacity, Gap Acceptance, Follow-up Headway, Critical Headway, Critical Gap, Circulation Road, Headway Distribution, Bunching, Queue, Trajectory

1 Introduction

*“Experience without theory is blind,
but theory without experience is mere intellectual play.”*
Immanuel Kant (1724 – 1804)

Gap acceptance theory has been applied to a vast range of road traffic situations where one movement yields (gives way) to another which is a key aspect of traffic operations. These include roundabouts, two-way stop and give-way (yield) control, signalised intersections (permitted turns, turn on red), unsignalised bypass (slip) lanes, merge lanes, vehicles yielding to pedestrian movements, and so on.

A large number of capacity models based on gap acceptance theory and calibration using various field survey methods have been reported in the literature [1-11]. Calibration of these models focuses on the follow-up headway and critical gap (headway) parameters for minor (opposed) traffic movements and the headway distributions for the major (opposing) traffic.

Two basic approaches exist for the calibration of gap acceptance models. The first approach uses *capacity surveys* to determine the *implied* follow-up and critical gap parameters and headway distributions, which may be associated with theoretical capacity model forms [1-4]. The second approach uses surveys of the follow-up and critical gap parameters and headway distributions for their use in models based on theoretical derivations [6-9]. The models are generally selected on the basis of statistical fitness measures with attention to the model's ability to perform well in specific situations.

Capacity models for single lane and multi-lane roundabouts are of particular interest. This report describes a new gap acceptance capacity survey method applied to a single-lane roundabout using detailed vehicle trajectory data. The survey uses gap acceptance cycles based on a traffic signal analogy approach as used for gap acceptance capacity and performance model development [10-11]. This concept represents the blocked and unblocked periods of vehicle entries as virtual contiguous red and green periods that act as gap acceptance cycles. In addition, the survey method allows measurement of follow-up and critical headway parameters and capacity of entry lanes *simultaneously* on a *cycle-by-cycle* basis.

Real-world vehicle trajectory data were collected at a single-lane roundabout with moderate volume conditions in Raleigh, NC, USA. Recent advances in GPS, drone, and image processing technologies have made it easier to access vehicle trajectories. Various public open-source trajectory datasets collected at different roundabouts are available [12-14]. By taking advantage of trajectory data, previous research has assessed roundabout capacity and performance [15, 16], analysed driver behaviour [17], and studied safety [18]. Chun [19, 20] estimated roundabout gap acceptance parameters using trajectory data extracted from drone video to calibrate analytical and simulation models. This research revealed that drone video and trajectory data provide sufficient information for the calibration and validation of traffic models.

The survey method defines *reliable gap acceptance cycles* as those with *saturated unblocked periods* which occur when *all entry vehicles are queued*. The results compared well against values obtained from some established methods. Average blocked time, unblocked time and gap acceptance cycle time estimates were assessed by applying the observed follow-up and critical headway values to M3D, M3B, M3T, M1 and M2 arrival headway distribution models [22-27]. Gap acceptance capacity estimates were assessed for these models as well as the Highway Capacity Manual (HCM) default roundabout capacity model [1-4] and the general Siegloch-M1 model used by HCM [5, 6, 8]. The results confirmed the validity of the survey method, supporting the novel signal analogy concept with real-world observations of gap acceptance cycles.

In *Section 3*, the background to the signal analogy concept used for deriving gap acceptance capacity and performance models is explained [10, 11]. The survey methodology is described in detail in *Section 4*. Detailed results from the survey using reliable gap acceptance cycles are given in *Section 5*. The implications of the survey results for calibrating roundabout capacity models are discussed in *Section 6*.

Survey results are discussed and various recommendations for future research are given in *Sections 7 and 8*.

2 Literature Review

This review is limited to the literature focused on gap acceptance theory for the purpose of estimating roundabout capacity. Other roundabout capacity models that do not use gap acceptance modelling are outside the scope of this report [29, 30].

Gap acceptance behaviour is best described by two key parameters: *follow-up headway* and *critical gap (headway)* [5-11]. Follow-up headway is the time interval between two entering, queued vehicles and the critical headway is the minimum gap that an entering vehicle is willing to accept. The estimation of these two parameters and the form of the gap acceptance model reflecting the opposing stream characteristics are crucial for calibration of the capacity model to reflect local traffic behaviour and other conditions at traffic facilities that operate according to gap acceptance rules.

Brilon et al [8] present a useful review of methods proposed in the literature for estimating of follow-up headway and critical gap parameters. Parameter estimation methods can be divided into two categories:

- (i) methods that calculate each parameter separately, and
- (ii) methods that estimate both parameters simultaneously.

In the first category, two methods commonly used are the Raff's method and Maximum Likelihood Estimation (MLE) method. Raff's method [8] assumes driver's homogeneity and defines the critical gap as the time headway at which vehicles have an equal likelihood of accepting or rejecting a given headway. In other words, the critical headway value is estimated using Raff's method as the point of intersection between the cumulative distributions of rejected and accepted gaps. To construct the cumulative distributions, surveys involving the collection of rejected gaps and accepted gaps are required.

The MLE method proposed by Troutbeck [8, 9] assumes that (i) the critical headway distribution is log-normally distributed, and (ii) that drivers are consistent, in that their accepted gap will always be at least as long as their largest rejected gap. Thus, a survey for MLE method requires the collection of the highest rejected gap and accepted gap for each entering vehicle.

Both Raff's and MLE methods are designed to estimate the critical gap, necessitating an additional survey to capture the follow-up headway. The average value of the collected observed follow-up headway is used for the purpose of capacity model estimation.

The Siegloch method [8], on the other hand, estimates both the follow-up and critical gap parameters simultaneously. This method estimates a regression line that represents the relationship between the accepted saturated headway and the number of vehicles entering the gap to estimate both the follow-up and critical gaps. Therefore, in order to collect the necessary data, the accepted gap (headway) size and the number of vehicles entering in each gap are collected through a survey method but only for saturated conditions, i.e. when all entry vehicles are queued. Since this condition is not easily observed in the field, it may be necessary to collect sufficient data during specific time periods. *Figure 2.1* shows an example of Siegloch estimation method and illustrates the parameters and their definitions.

The estimated parameters discussed above are used for calibrating various gap-acceptance-based roundabout capacity models.

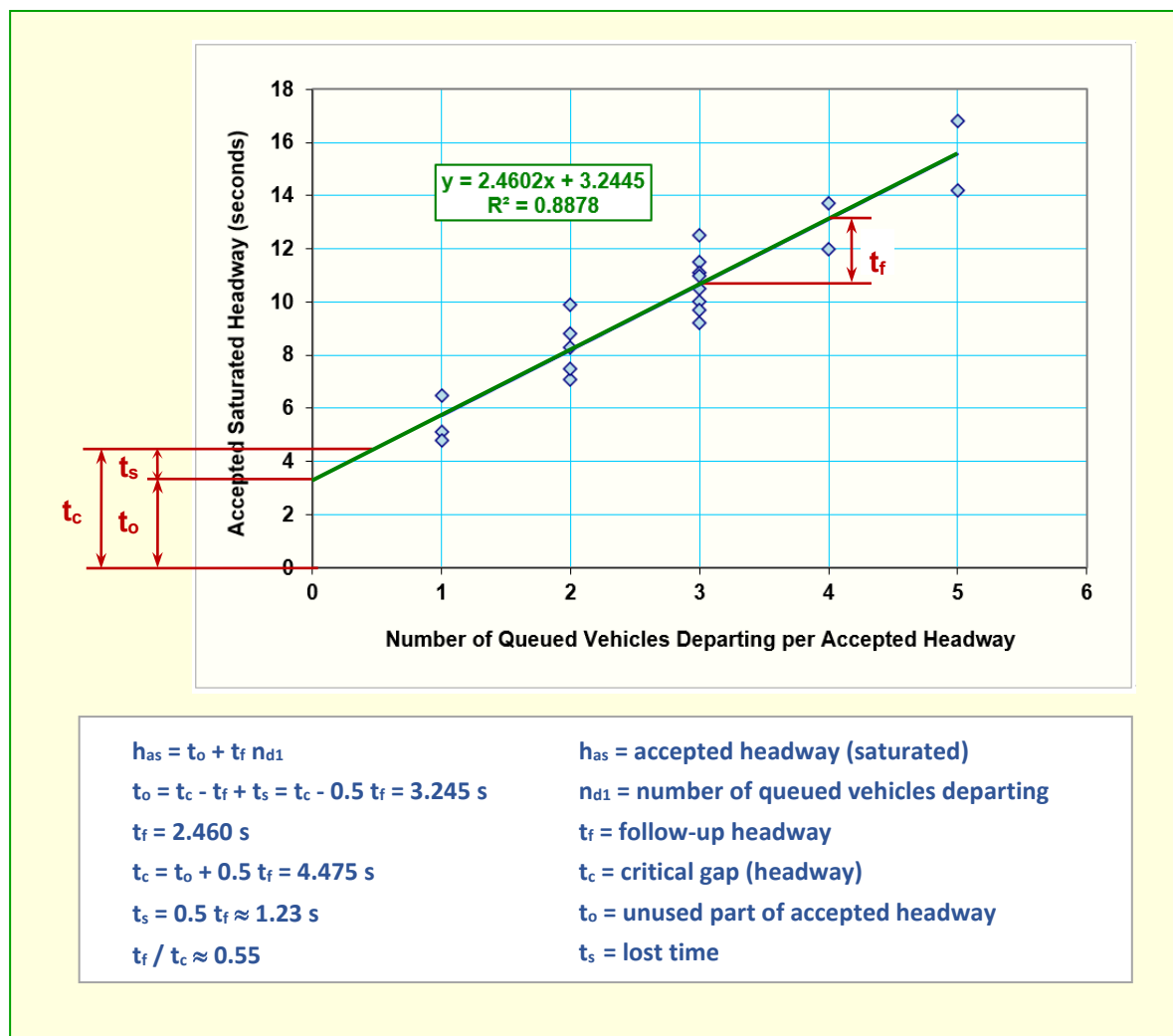


Figure 1.1 - An example of Siegloch parameter estimation method
(Source: *SIDRA Gap Acceptance Survey Excel application 19/5/25*
<https://support.sidrasolutions.com>)

3 Roundabout Capacity Model Using Gap Acceptance Cycles

3.1. Capacity Model Concept

The US Highway Capacity Manual (HCM) 7th edition includes a roundabout capacity model which has the same form as the Sieglösch capacity model [1-5, 10, 11, 32]. It assumes a negative exponential distribution of circulating headways. The following is a general form of the HCM capacity model, along with the default gap acceptance parameter values for a single lane roundabout:

$$Q_g = f_p f_{HV} (3600 / t_f) e^{-q_c t_o} \quad (3.1)$$

where

Q_g = entry lane capacity (veh/h),

t_f = follow-up headway (s), HCM default = 2.61 s,

t_c = critical headway (s), HCM default = 4.98 s,

t_o = unused part of accepted headway, $t_o = t_c - 0.5 t_f$ (s), HCM default = 3.67 s,

q_c = opposing (circulating) flow rate adjusted using opposing vehicle factor values of heavy vehicles and other movement classes in the circulating flow (pc/s),

f_{HV} = heavy-vehicle factor for the entry lane determined using gap acceptance factor values of the approach movements including heavy vehicles and other movement classes in the entry lane,

f_p = pedestrian impedance factor for the effect of pedestrians crossing in front of entry lanes.

For roundabout entry lanes, Akçelik [10, 11] introduced a new concept for capacity and performance estimation at roundabouts, drawing an analogy to capacity estimation at traffic signals. In gap acceptance theory, as illustrated in *Figure 3.1*, consecutive short circulating arrival headways prevent gap acceptance while vehicles are queued during *block time* (t_b), and queued vehicles depart when an acceptable headway occurs during *unblock time* (t_u). Signal analogy concept converts these parameters to *effective blocked time* ($r = t_b - t_f + l$) similar to effective red time at signals, and *effective unblocked time* ($g = t_u + t_f - l$) similar to effective green time at signals. The *gap acceptance cycle time* is the sum of these parameters ($c = t_b + t_u = r + g$).

The model assumes that (i) the first queued vehicle departs t_f seconds after the start of the acceptable headway, and (ii) the last queued vehicle departs $t_o = l + t_c - t_f$ seconds before the end of the acceptable headway. Parameter t_o is the unused part of the acceptable headway. It includes the lost time determined approximately as half the follow-up headway ($l = 0.5 t_f$), therefore $t_o = t_c - 0.5 t_f$. This parameter appears in the HCM model given by *Equation (2.1)*. The lost time (l) is due to an integer number of vehicles depart with the follow-up headway t_f .

An example is also presented in *Figure 3.1* which depicts entering vehicles giving way (yielding) to uninterrupted circulating vehicles. Although not depicted in the figure, the last vehicle entering in the previous cycle crossed the give-way line at time $t_1 - t_o$. The next vehicle came to a stop to avoid a collision with the first circulating vehicle that arrived at time t_1 , waiting for a gap until time t_5 . As a result, the effective blocked time (r) in the cycle is estimated as $t_5 - t_1 + t_o$. Once the first vehicle at the yield line can accept a gap beyond t_5 , the effective unblocked period starts at that moment. This period extends to the point at which the sixth queued vehicle crosses the yield line, marking the start of the next gap acceptance cycle and the beginning of the next effective blocked period. Thus, the effective unblocked time is $g = t_6 - t_5 - t_o$ and the cycle time is $t_6 - t_1$.

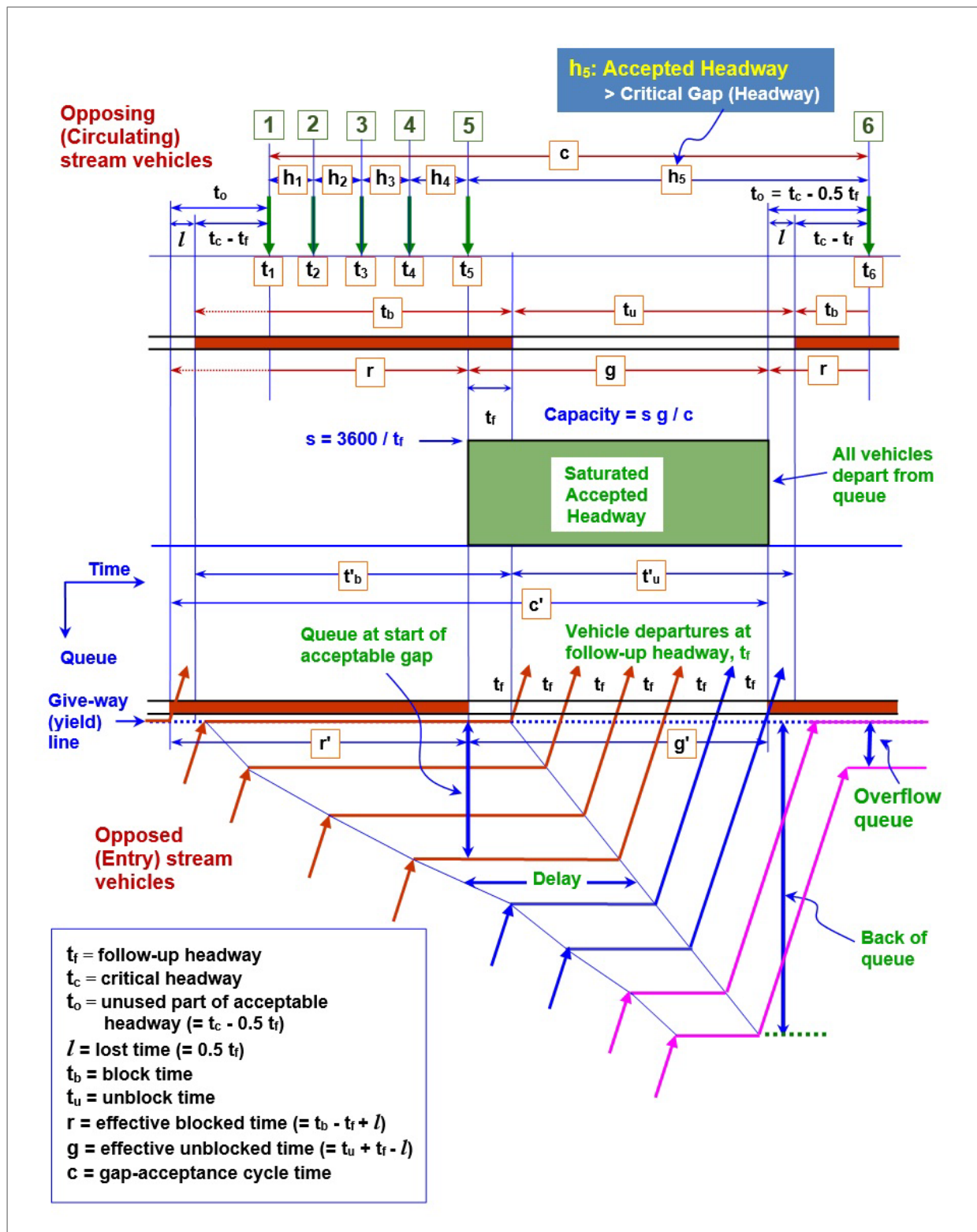


Figure 3.1 - A gap acceptance cycle based on signal analogy concept (Akçelik [5, 10, 11])

3.2 Gap Acceptance Capacity Model

Using the signal analogy concept, Akçelik [10, 11] developed equations to estimate the effective blocked time, effective unblocked time, the gap acceptance cycle time and related parameters as shown in Equations (3.2) to (3.6). This concept allowed the development of new gap acceptance capacity models as well as performance models for estimating delay, queue length (at the start of acceptable headway and back of queue) and stop rate for roundabouts and unsignalised intersections. These performance models have been in use in the SIDRA INTERSECTION software since the 1990s [31].

$$r = e^{\lambda(t_c - \Delta_c)} / (\phi_c q_c) - (1 / \lambda) - 0.5 t_f \quad (3.2)$$

$$g = (1 / \lambda) + 0.5 t_f \quad (3.3)$$

$$c = r + g = e^{\lambda(t_c - \Delta_c)} / (\phi_c q_c) \quad (3.4)$$

$$u = g / c = (1 - \Delta_c q_c + 0.5 \phi_c q_c t_f) e^{-\lambda(t_c - \Delta_c)} \quad (3.5)$$

$$Q_g = s u = s (g / c) = (3600 / t_f) (g / c) \quad (3.6)$$

$$= (3600 / t_f) (1 - \Delta_c q_c + 0.5 \phi_c q_c t_f) e^{-\lambda(t_c - \Delta_c)}$$

where

r = effective blocked time (s),

g = effective unblocked time (s),

c = gap-acceptance cycle time (s)

$u = g / c$ = effective unblocked time ratio (proportion of time when vehicles depart from the queue)

Q_g = gap acceptance capacity for the entry lane (veh/h),

t_f = follow-up headway (s)

t_c = critical headway (s),

q_c = opposing (circulating) flow rate (pc/s),

Δ_c = minimum headway in the circulating stream (s),

ϕ_c = proportion of unbunched (free) vehicles (see Table 3.1),

λ = model parameter calculated from

$$\lambda = \phi_c q_c / (1 - \Delta_c q_c) \quad \text{subject to } q_c \leq 0.98 / \Delta_c \quad (3.7)$$

In Equation 3.6, it is seen that the basic capacity equation $Q_g = s (g / c)$ is similar to the signalised intersection capacity equation where s is the saturation flow rate and g / c is the effective green time ratio. It is important to emphasise that the capacity model presumes that entry queued vehicles are present at both the start and the end of a cycle (i.e. a fully saturated cycle).

Figure 3.1 shows two different definitions of the *gap acceptance cycle*. **Cycle time c** is based on *circulating vehicles*, and **cycle time c'** is based on the *entry vehicles*. The definition based on the *circulating vehicles* shown as c at the top part of the figure is relevant to the definition of cycle capacity with the *unused part of the accepted headway*, t_o for the cycle shown at the end of the cycle:

$$t_o = t_c - 0.5 t_f \quad (3.8)$$

Therefore, the blocked time (t_b) is divided into two periods around the unblocked time, and the effective red time (r) is also defined as two separate periods at the beginning and end of the cycle. Because of the cyclic nature of data, the average values of gap acceptance cycle parameters would be close.

The definition of the gap acceptance cycle based on the *entering vehicles* shown as c' in the middle part of Figure 3.1 is relevant to the modelling of queuing of the approach (entry) vehicles. This definition shows the t_o parameter which belongs to the previous cycle as part of the effective blocked (red) time of the current cycle. In Figure 3.1, the t_o parameter as an average value is the same for the previous and the current cycles, therefore the cycle time is identical for the two definitions. However, in the survey method, t_o values for consecutive cycles will not be the same. This is discussed in Section 5 (*Survey Methodology*) with an example given in Figure 5.1.

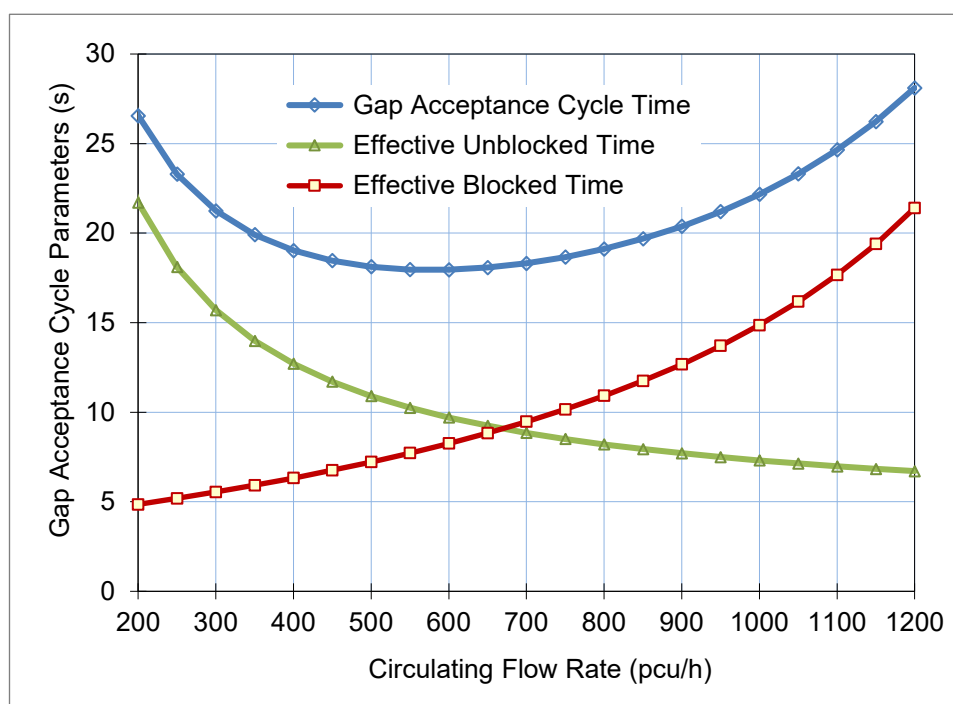


Figure 3.2 - The blocked and unblocked times and the gap acceptance cycle time as a function of the circulating flow rate for the HCM capacity model parameters for a single-lane roundabout (estimated using Akçelik-M3D model)

Figure 3.2 shows the blocked and unblocked times and the gap acceptance cycle time from Equations 3.2 to 3.4 as a function of the circulating flow rate. The graphs in this figure are derived for the Akçelik-M3D model (discussed below) using the HCM follow-up headway and critical gap defaults for a single-lane roundabout (follow-up headway = 2.61 s and critical headway = 4.98 s).

3.3 Bunching in Opposing (Circulating) Flow

The gap acceptance capacity models vary according to the assumption regarding the distribution of arrival headways in the opposing flow (circulating flow for roundabouts) [5]. This includes the Akçelik-M3 capacity model based on the *bunched exponential* headway distribution described by Cowan [22, 33].

Table 3.1 shows four different **bunching models** which can be used in the Akçelik-M3 model. For this model application, a **bunching model** is needed to estimate the *proportion of unbunched (free) vehicles in the traffic stream* (ϕ_c) using a *minimum (intra-bunch) headway* ($\Delta_c > 0$) parameter. Five different bunching models are given below. Default parameter values for the Akçelik-M3 capacity models for multi-lane roundabouts are given in Table 3.2.

The M3D, M3DS, M3A, M3T and M3B models in Table 3.1 are bunched exponential headway distributions with different *bunching models* used to estimate the *proportion unbunched*, ϕ_c [5, 10, 11, 22, 24-27]. These models as well as the M1 and M2 models are described below:

- The M3D model uses a *delay parameter*, k_d . Lower values of k_d give lower levels of bunching and lower capacities (increased bunching causes an increase in capacity).
- The M3DS is the *shifted bunched exponential* model using the delay parameter [5].

- The M3T model uses a *linear bunching model* which can be considered as a special case of the *bunched exponential model* where $k_d = 1.0$. The function appears as if it does not use the delay parameter, k_d . This is known as Tanner's model [23].
- The M3B model uses a *bilinear bunching model* which can be considered as a special case of the *shifted bunched exponential model* where $k_d = 1.0$. The function appears as if it does not use the delay parameter, k_d . The bilinear bunching model was described by Vasconcelos et al [27]. Using the Akçelik model for capacity (Equation 3.6), the model is referred to as Akçelik-M3B capacity model in this report.
- The M3A model uses an *exponential bunching model* [5]. This is an older model which has not been used in this report.
- The simple *negative exponential headway (M1)* model assumes $\Delta_c = 0$, $\varphi_c = 1.0$ (therefore $\lambda = q_c$), and the *shifted negative exponential headway (M2)* model ($\Delta_c > 0$) assumes $k_d = 0$ or $\varphi_c = 1.0$ and $\lambda = q_c / (1 - \Delta_c q_c)$.
- The *Akçelik-M1* and *Akçelik-M2* capacity models are obtained using the parameters based on these assumptions in Equations (3.1) to (3.6).

Figure 3.3 shows a comparison of capacity estimates from Equation (3.6) for different circulating flow headway distributions (M3D, M3DS, M3B, M3T, M1 and M2) using the US HCM capacity model parameters for a single-lane roundabout ($t_f = 2.61$ s, $t_c = 4.98$ s) and the parameters shown in Tables 3.1 and 3.2 for the bunched exponential models M3D, M3DS, M3B and M3T. Note that the effects of *unbalanced flows* and the *entry flow / capacity flow ratio* are not included in these estimates. Minimum capacity of 150 pc/h is applied to all models.

The results show that there is little difference between models at low circulating flows, while the differences increase with an increase in circulating flow, and the impact of the bunching model (assumption about the arrival headway distribution) is significant at high circulating flow levels.

Table 3.1 - Bunching models compatible with the Akçelik-M3 gap acceptance capacity model (Equation 3.6)

Bunching Model	Bunching Model to Estimate Proportion Unbunched, φ_c
M3D	$\varphi_c = (1 - \Delta_c q_c) / (1 - (1 - k_d) \Delta_c q_c)$ ($k_d = 2.2$ for roundabouts)
M3DS	$\varphi_c = [(1 - \Delta_c q_c) / (1 - \Delta_c q_L)] / [1 - (1 - k_d) \Delta_c (q_c - q_L)]$ for $q_c > q_L$ = 1.0 otherwise q_L is the limiting flow rate (pc/s) above which $\varphi_c < 1.0$ ($q_L = 166$ pc/h). ($k_d = 0.8$ for roundabouts)
M3B	$\varphi_c = (1 - \Delta_c q_c) / (1 - \Delta_c q_L)$ for $q_c > q_L$ = 1.0 otherwise q_L is the limiting flow rate (pc/s) above which $\varphi_c < 1.0$ ($q_L = 641$ pc/h). (equivalent to $k_d = 1.0$ in M3DS)
M3T	$\varphi_c = 1 - \Delta_c q_c$ (Equivalent to $k_d = 1.0$ in M3D)
M3A	$\varphi_c = \exp(-b \Delta_c q_c)$ ($b = 2.5$ for roundabouts)
Minimum Headway	$\Delta_c = 2.0$ s for single-lane roundabouts (all models)

Minimum value $\varphi_c \geq 0.1$ used in *SIDRA INTERSECTION* is not applied in this report.

Table 3.2 - Default parameter values for estimating the proportion of unbunched circulating vehicles (M3 models)

Number of circulating lanes	Δ_c	$3600 / \Delta_c$	k_d	b
1	2.0	1800	2.2	2.5
2	1.0	3600	2.2	2.5
>2	0.8	4500	2.2	2.5

Source: Akçelik [5]

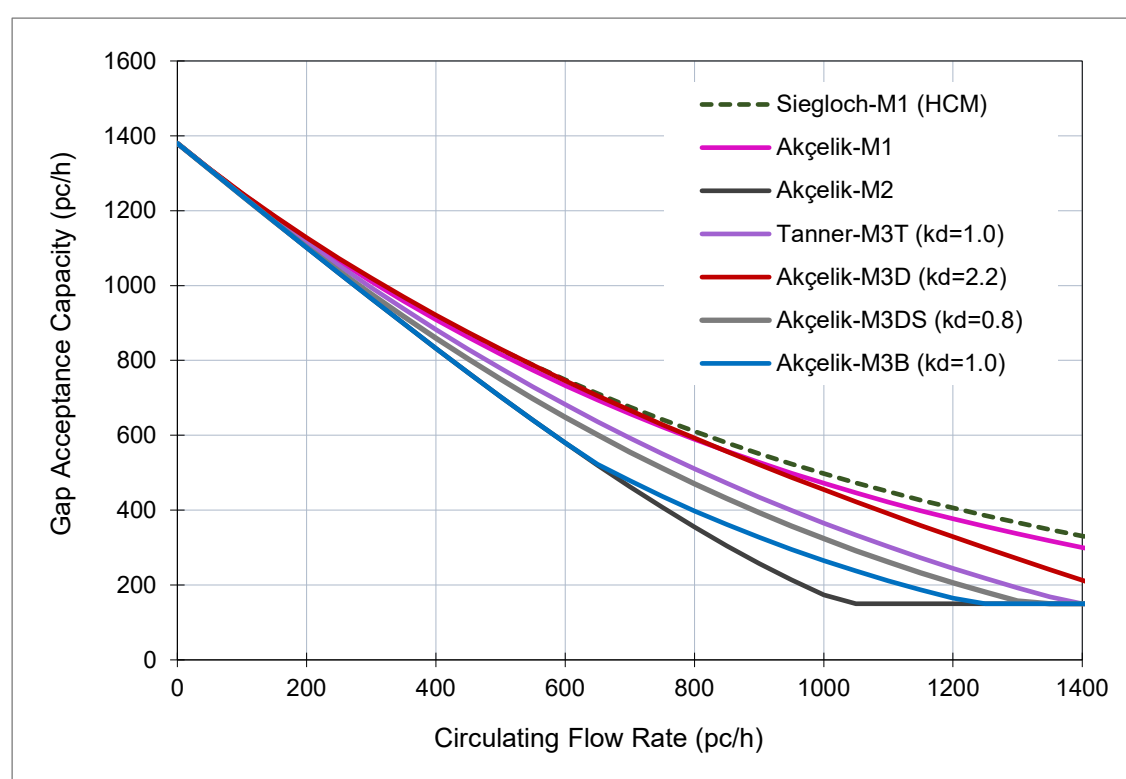


Figure 3.3 - Capacity estimates for Akçelik M3D, Akçelik-M3B, M3T, M1 and M2 models using the HCM capacity model parameters for a single-lane roundabout (minimum capacity of 150 pc/h applied)

4 Data Preparation

4.1 Site Description and Data Collection

A single lane roundabout was used to develop and assess a new roundabout survey method that uses gap acceptance cycles based on a traffic signal analogy approach. The roundabout is located near the NC State University campus in Raleigh, NC, USA (*Figure 4.1*). Of interest in this study are the Southbound (SB) and Eastbound (EB) approaches. Both include a slip right turn lane and a single shared through and left lane. In all the analyses that follow, the focus is on the shared through and left lanes. The Eastbound approach is on the path of school bus routes. However, the results given in this report exclude the gap acceptance cycles with heavy vehicles, including buses, due to an insufficient number of such cycles for meaningful analysis. In addition, cycles involving pedestrians were also excluded from the analysis.

Data collection was carried out primarily during the PM peak period (from 4:40 to 6:00 pm) using videos captured from a drone operating at a height of approximately 400 ft.

The operation of a drone can be categorized into two methods based on the power supply: tethered and untethered. The first method involves physically connecting the drone to a power source on the ground, while the latter relies on a battery to supply power. The videos used in this study were captured using the untethered method. Although continuous video recording was not possible due to battery limitations (about 10-12 minutes per flight), considering that gap acceptance parameters are independent of time, the untethered method can cover a wider range of operations compared to the tethered method and neither has much of an impact on driver gap acceptance behaviour. In total, eight video recordings yielding a bird's-eye view of the operation were taken, each approximately 10 minutes in length. As shown in *Figure 4.1*, the field of view enabled the tracking of each entry and circulating vehicles for the SB and EB approaches from arrival to departure.

4.2 Data Extraction

To ensure precise, robust, and cost-effective data extraction, the task of video processing is outsourced to the company DataFromSky or DFS (DataFromSky, 2022). DFS employs advanced computer vision techniques to extract high-resolution vehicle trajectories and offers the users a unique software tailored for post-processing the extracted data.

The DFS trajectory extraction framework encompasses four main steps. Firstly, a pre-processing step readies the available videos for data extraction. During this phase, DFS typically requires analysts to either cut the video during non-hovering periods or stitch together multiple videos. Secondly, the video stabilization step addresses the natural shakiness of the UAV while in flight. Perspective transformation is carried out on each video frame using an eight-degree-of-freedom homography, and RANdom SAmples Consensus (RANSAC) estimates the parameters while Oriented fast and Rotated Brief (ORB) algorithms extract critical points. Subsequent to stabilizing the video, vehicle detection takes place using two-stage detectors (e.g., Fast R-CNN or Faster R-CNN). Next, the trajectories of each detected vehicle are smoothed using a vehicle kinematic model. Finally, geo-referencing converts the pixel-based trajectory data into latitude and longitude coordinates. Geo-referencing can be readily achieved using a minimum of four reference points within the drone footage area. *Figure 4.1* shows the overlapping vehicle trajectories, vehicle IDs and speeds, as extracted from the video alongside the drone footage. Note that all vehicle trajectories are updated at a 1/30 sec resolution.

In the eight videos analysed, a total of 1,939 vehicle trajectories were extracted. Among them, 903 vehicles accepted a gap in both the shared through and left lane on the SB or EB approach. The vehicle classification on the SB and EB approaches utilizing the shared lane is summarized in *Table 4.1*. On average, vehicles in the circulating lane travelled at a speed of 16.44 mph (26.5 km/h), and at a speed standard deviation of 2.3 mph (3.7 km/h).

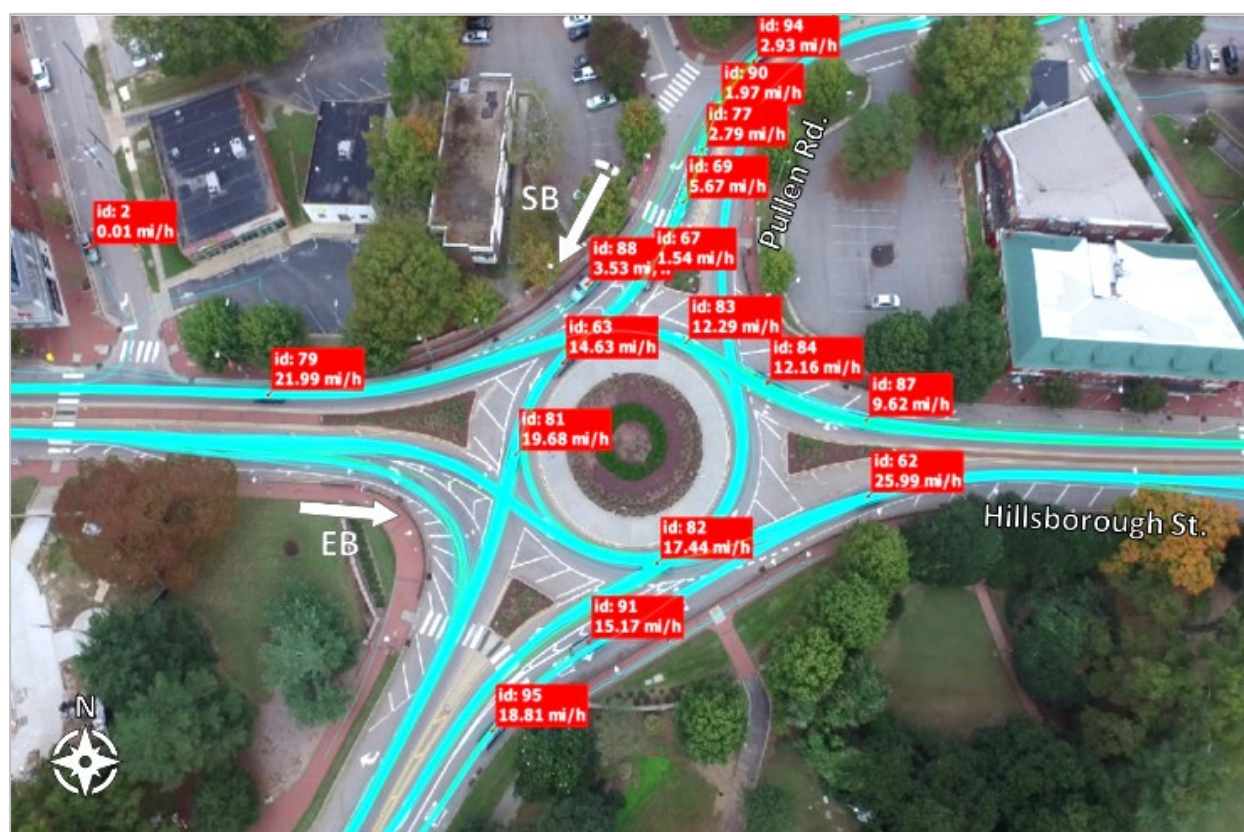


Figure 4.1 - Processed drone video screenshot showing individual vehicle IDs and their speeds

Table 4.1 - Vehicle classification at the Southbound and Eastbound approaches

Vehicle Class	Description	Southbound Approach		Eastbound Approach	
		Number	Percent	Number	Percent
Passenger car	Passenger cars + Other two-axle trucks	468	98.5%	404	94.4%
Heavy vehicles	Buses + Three or more axle trucks	5	1.1%	13	3.0%
Two-wheeled vehicles	Motorcycles + Bicycles	2	0.4%	11	2.6%
Total		475	100%	428	100%

5 Survey Methodology

Unlike the theoretical and idealized gap acceptance framework illustrated in *Figure 3.1*, analysts can encounter ambiguous cases in the process of determining gap acceptance cycles. That process requires the filtering of cycles that can be used for the analysis in field observations. As such, a clear and precise definition of a useable (reliable) gap acceptance cycle and the specification of rules for determining a cycle's suitability for analysis are necessary. This chapter describes the definition and the rules developed in this research when one uses empirical observations. In addition, key statistics estimated from the gap cycles selected are also presented.

5.1 Gap Acceptance Cycle Attributes from Empirical Observations

The definition of a gap acceptance cycle as illustrated in *Figure 3.1* implies that queued vehicles *must be* available to use the *entire* green time or unblocked period. Thus, an important consideration when working with observed vehicle trajectories is to be able to distinguish between those cycles where one or more queued vehicles are available to fully use the circulating flow gap and other cycles where there are unused periods within the cycle. In the notation that follows, we will use the term “*reliable cycle*” to describe the former condition. In addition, there must be a precise and consistent definition of the time when each cycle starts and ends (reliable or otherwise). This is not a trivial task when one deals with real world rather than theoretical trajectories.

In *Figure 3.1*, two different *gap acceptance cycle* definitions were shown. These are also shown in *Figure 5.1*. The data analyses described in this report were carried out using the definition based on the *circulating vehicles* due to its practicality and ease of data collection. This definition, which is relevant to the definition of cycle capacity, measures the *unused part of the accepted headway*, $t_{o(i)}$ at the end of the subject (*ith*) cycle, c .

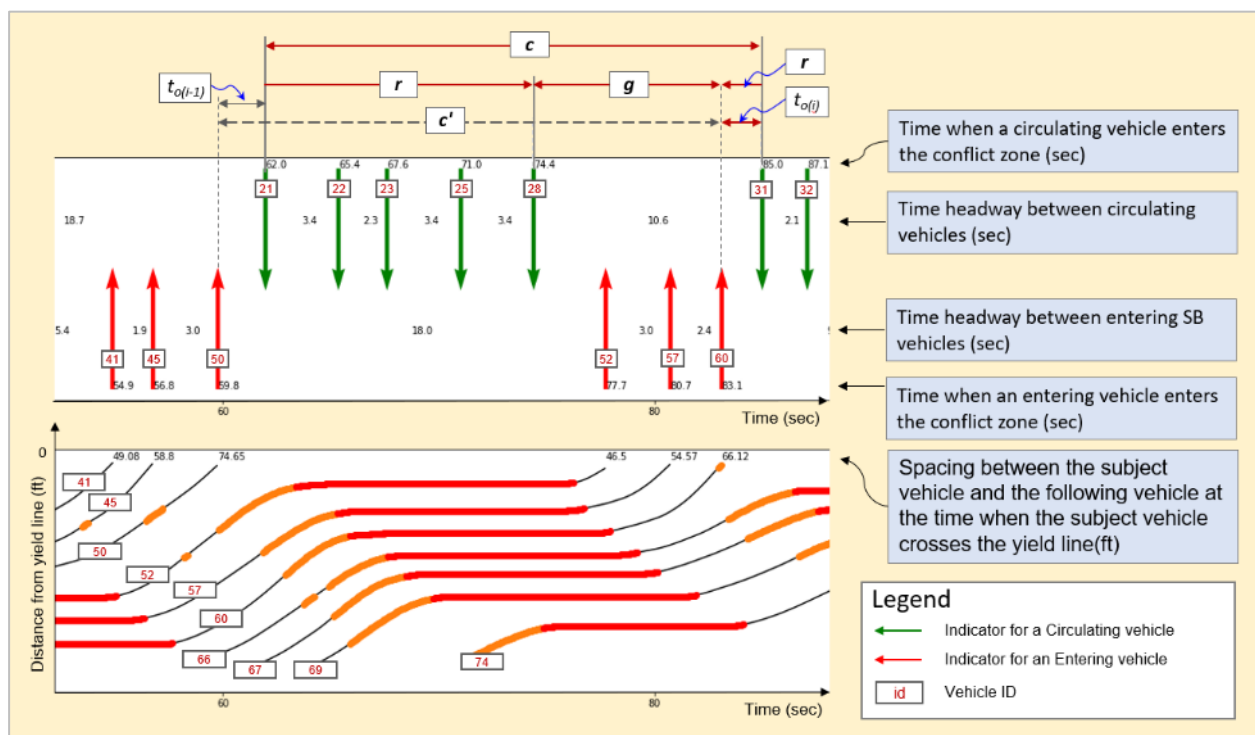


Figure 5.1 - Illustration of gap acceptance cycle attributes from empirical observations

For use in modelling of queuing of approach (entry) vehicles, $t_{o(i-1)}$ which belongs to the previous cycle is used as part of the effective blocked (red) time of the current cycle as indicated in *Figures 3.1 and 5.1*. The population and the average values of t_o are the same irrespective of the gap acceptance cycle definition. However, in the survey method, $t_{o(i)}$ and $t_{o(i-1)}$ values for consecutive cycles will not be the same. This is discussed with reference to the example given in *Figure 5.1*.

Figure 5.1 shows a time-space representation for a sample of vehicle trajectories extracted from drone videos on the SB approach. Although one may visually consider the indicated cycles to be reliable, it is premature to make such a definite call without first setting some clear rules and criteria that are given in the next section. This section demonstrates how the information was extracted for each gap acceptance cycle including the unblocked (green) and blocked (red) time parameters. This process follows the same definitions as depicted in *Figure 3.1*. The numbered labels shown in *Figure 5.1* are explained below. Refer to *Figure 5.2* for the reference lines that define the conflict zone on the circulating road.

Figure 5.1 has an upper and lower part. The upper part illustrates the entering and circulating vehicle arrivals in the conflict zone. The red arrows indicate the times when the entry (or approach) vehicles pass the effective yield line, while the green arrows represent circulating vehicles at the point they cross the reference line in the circulating lane. The blue arrows and grey coloured values between the red and green arrows indicate the time headway for each vehicle. The lower part of *Figure 5.1* depicts the full trajectory of each entering vehicle. Here the orange colour indicates that the vehicle is decelerating, $v(t+1) < v(t)$, and the red colour represents a complete stop, which is in this context means $v(t) \leq 3$ mph.

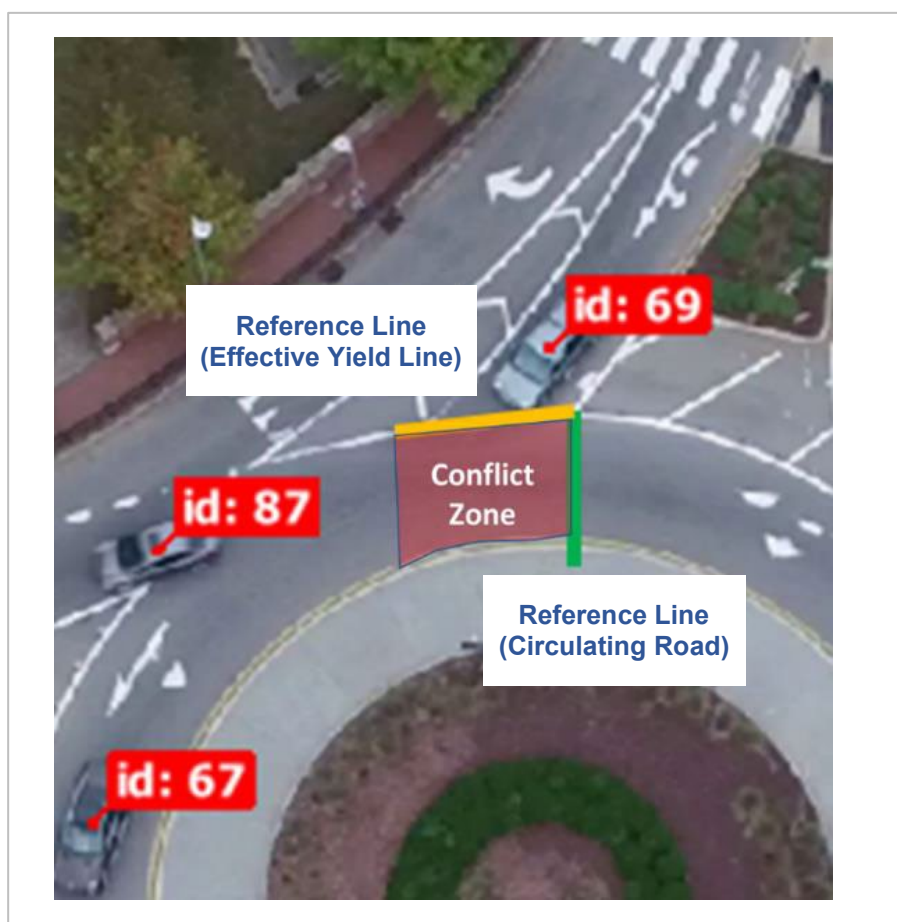


Figure 5.2 - Reference Lines for conflict zone shown for the Southbound approach

In the example shown in *Figure 5.1*, the subject (*i*th) gap acceptance cycle starts at time $t = 62.0$ s and ends at time $t = 85.0$ s, yielding a cycle time of $c = 23.0$ s, according to the gap acceptance cycle definition used for data analyses. The time $t = 62.0$ s also represents the end of the previous cycle (*i-1*), and the time $t = 85.0$ s also represents the start of the next cycle (*i+1*).

In this example, the *effective unblocked (green) time* represents the duration between the last circulating vehicle in the cycle (74.4 s) and the last entering vehicle (83.1 s), giving $g = 8.7$ s. The *accepted headway* is the time between the last circulating vehicle in the subject cycle and the first circulating vehicle in the next cycle, $85.0 - 74.4 = 10.6$ s. Thus, the *unused part of the accepted headway*, $t_{o(i)} = 10.6 - 8.7 = 85.0 - 83.1 = 1.9$ s. For the previous cycle, $t_{o(i-1)} = 62.0 - 59.8 = 2.2$ s.

The effective blocked (red) time is calculated by subtracting the effective unblocked time from the gap acceptance cycle time, $r = c - g = 23.0 - 8.7 = 14.3$ s. This is the method used in the data analyses, which follows. Conversely, the effective blocked (red) time calculated using the unused part of the accepted headway, $t_{o(i-1)}$ for the previous cycle is $r = c' - g = (c - t_{o(i)} + t_{o(i-1)}) - g = 23.0 - 1.9 + 2.2 - 8.7 = 23.3 - 8.7 = 14.6$ s.

As discussed above, the population and the average values of the t_o parameter are the same irrespective of the gap acceptance cycle definition, and therefore the data analyses method used gave average values and distributions of cycle time, red time, critical headway and cycle capacity that are similar. The effective unblocked time and follow-up headway (g , t_f) are not affected by the gap acceptance cycle definition.

In addition to the effective blocked and unblocked times (r , g) and the unused part of the accepted headway (t_o), the gap acceptance parameters follow-up headway and critical headway (t_f , t_c), the circulating flow rate (q_c) and the capacity, Q_g for a *fully saturated cycle* are calculated as follows:

$$t_f = g / n_e \quad (5.1)$$

$$t_c = t_o + 0.5 t_f \quad (5.2)$$

$$q_c = 3600 n_c / c \quad (5.3)$$

$$Q_g = (3600 / t_f) g / c = 3600 n_e / c \quad (5.4)$$

where

g = effective unblocked time (s),

c = gap-acceptance cycle time (s),

t_o = unused part of the accepted headway (s),

n_e = number of queued vehicles entering the circulating road during the *accepted headway* (this does not include the first vehicle in the next cycle),

n_c = number of circulating vehicles crossing the reference line during the gap acceptance cycle,

q_c = circulating flow rate (pc/h),

Q_g = capacity (pc/h),

In the example in *Figure 5.1*, the cycle length $c = 85 - 62 = 23$ s, $g = 8.7$ s, $n_e = 3$, $n_c = 5$ are all observed. Using these values, *Equations 5.1 to 5.4* give: $t_f = 8.7 / 3 = 2.90$ sec, $t_c = 1.9 + 0.5 \times 2.90 = 3.35$ s, $q_c = 3600 \times 5 / 23.0 = 783$ pc/h and $Q_g = (3600 / 2.90) \times (8.7 / 23.0) = 3600 \times 3 / 23.0 = 470$ pc/h.

5.2 Rules for Reliable Cycles

This section specifies the conditions that must be met in order to identify and extract the set of reliable cycles from the population of field-observed gap acceptance cycles. This process is necessary to meet the need for estimating the critical gap, follow up headway and capacity values based on empirical observations.

The first key question in determining a *reliable cycle* is the definition of a *queued vehicle* in a *saturated cycle*. The following sections focus on this definition with the help of a concept diagram. Of course, the actual rules and criteria are determined based strictly on empirical observations.

5.2.1 Rules for gap acceptance surveys

In addition to the condition regarding *queued vehicles* and *saturated cycles* (**Rule 1** below), there are additional rules in the gap acceptance survey data that should be considered carefully for the calibration of a gap acceptance capacity model (see *Figure 5.3*).

- **Rule 1:** All entering vehicles in a reliable cycle are *queued* and the cycle is *saturated*.
 - **Condition 1.a:** There must be *at least one queued vehicle at the start of the cycle*.
 - **Condition 1.b:** All vehicles entering after the first vehicle, including the last vehicle, must be *queued*.
 - **Condition 1.c:** The cycle must be *saturated*.

All three conditions *must be satisfied* for **Rule 1** to be satisfied.

- **Rule 2:** All queued vehicles entering in a cycle must cross the effective yield line (*Figure 5.2*).
- **Rule 3:** No entering vehicle in a reliable cycle should be impacted by pedestrian presence.
- **Rule 4:** Cycles in which vehicle movement classes other than Light Vehicles should be included or excluded from the analysis with care, depending on the analysis objective.

Rules 2 and 3 are applied by direct field observation. **Rule 4** requires separate analyses (i) with Light Vehicles only and (ii) with other vehicle movement classes (Heavy Vehicles, Buses, Bicycles, Large Trucks) in entering flow and in circulating flow included selectively. In this analysis, the number of reliable cycles involving non-passenger cars was limited to five for both the SB and EB approaches. Therefore, due to the insufficient sample size, the analysis focused exclusively on passenger cars to ensure data reliability when estimating gap acceptance parameters. However, an illustrative method for estimating Heavy Vehicle Gap Acceptance Factor is given in the Appendix.

5.2.2 Conditions and Numerical Criteria for Queued Vehicle Definition

Surveys at roundabouts and intersections controlled by *give-way/yield signs* aim to determine the gap acceptance capacity at the same time as the key parameters used in capacity estimation, namely the critical gap (headway) and follow-up headway. This requires observation of vehicles departing from a queue. Thus, the definition of a queued vehicle is important for the purpose of gap acceptance surveys. These criteria also apply to saturation flow surveys at signalised intersections.

Vehicles departing from a queue during an acceptable gap in the opposing stream, or during a green period at signals, can be identified as those which are part of the *back of queue* and cross the give-way/yield or stop line at the *saturation headway* (follow-up headway in gap acceptance). The gap acceptance cycles or unblocked periods with *all vehicles* crossing the give-way line after joining the back of queue are defined as *saturated cycles* or *saturated unblocked periods*. Similarly, signal cycles or green periods with all vehicles crossing the stop line after joining the back of queue are defined as *saturated cycles* or *saturated green periods*.

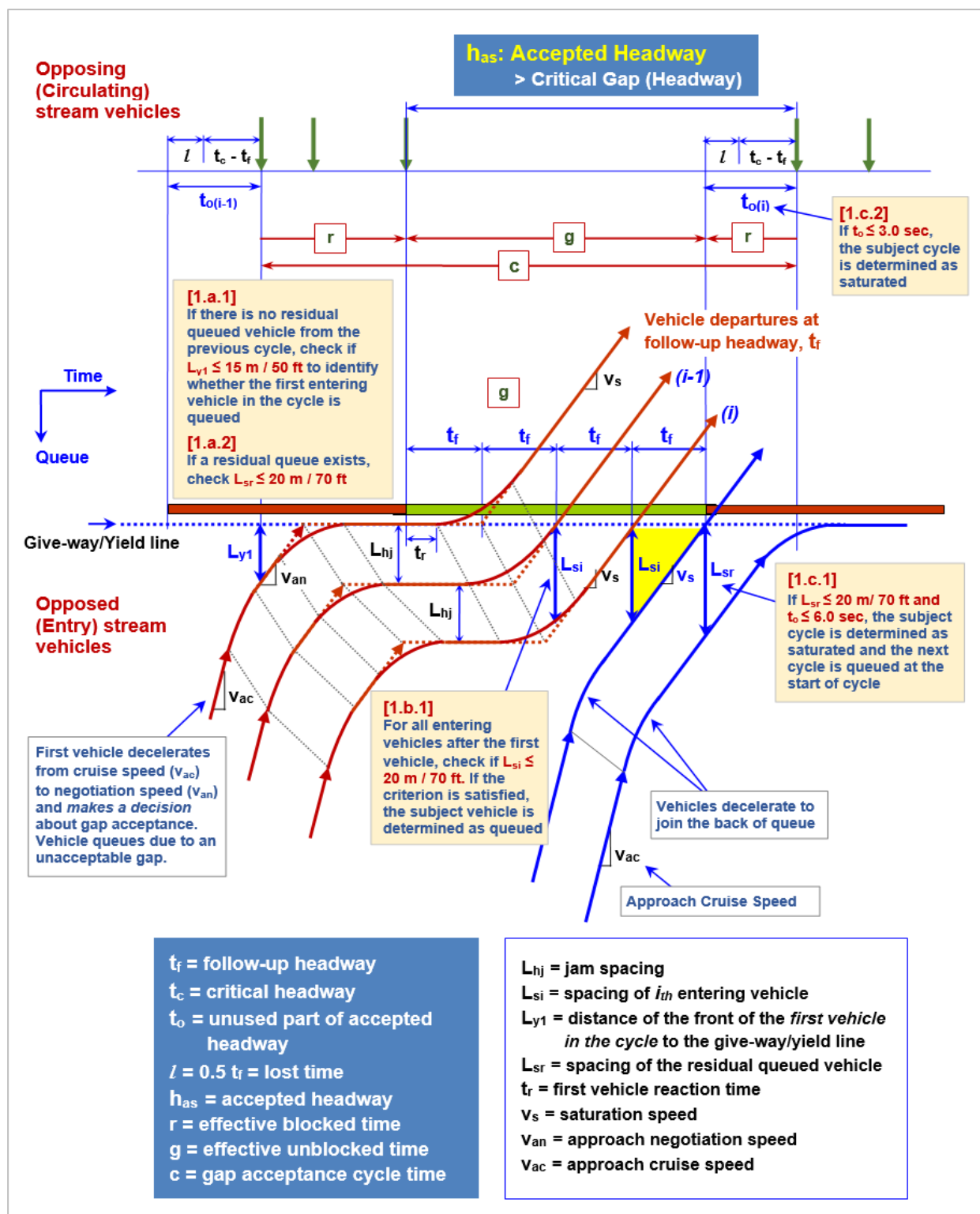


Figure 5.3 - Gap acceptance parameters to define "queued vehicle"

Some complications arise in defining a *queued vehicle* and a *saturated cycle*. The queue length named as the *back of queue* includes vehicles that are *stopped* as well as vehicles that *slow down* at the back of queue without coming to a full stop but cross the give-way or stop line at the saturation (follow-up) headway. At intersections controlled by give-way/yield signs (as opposed to stop signs), vehicles are not expected to stop. There are also gap acceptance situations such as a *freeway merge* where no vehicles are fully stopped and are traveling at high speeds as they accept gaps in the opposing stream.

It is relatively easy to identify *stopped vehicles*, e.g. using a criterion such as *speed* less than around 3 mile/h. However, it is more difficult to define a criterion to identify *vehicles slowing down at the back of queue* as "queued" or "unqueued" since the speed of these vehicles can be quite high. At roundabouts and intersections controlled by give-way/yield signs, the safe *negotiation speed of unqueued vehicles* is close to the saturation speed. For this reason, a *saturation spacing* criterion is recommended for use in gap acceptance surveys at roundabouts and intersections controlled by give-way/yield signs. This is also recommended for saturation flow surveys at signalised intersections.

In gap acceptance processes, there are cycles when *all vehicles are queued* but it is not clear if the cycle is *saturated*. Supplemental conditions and criteria are used for this reason.

The **Conditions and Criteria for Rule 1 above** ("All entering vehicles in the cycle are *queued* and the cycle is *saturated*.") are as follows (see *Figure 5.3*, which is a concept diagram that includes references to the *Criteria* used as described next).

- *Condition 1.a and Condition 1.b and Condition 1.c* must be satisfied for **Rule 1** to be satisfied, i.e. for all entering vehicles in the cycle to be identified as *queued* and the cycle to be identified as *saturated*.
- *Criterion 1.a.1 or Criterion 1.a.2* must be satisfied for *Condition 1.a* to be satisfied.
- *Criterion 1.b.1* must be satisfied for *Condition 1.b* to be satisfied.
- *Criterion 1.c.1 or Criterion 1.c.2* must be satisfied for *Condition 1.c* to be satisfied.

Only gap acceptance cycles that satisfied all four rules (**Rule 1 to Rule 4**) were classified as reliable cycles, and only these reliable cycles were used for further analysis.

The Conditions and Criteria for **Rule 1** are described in detail below.

Condition 1.a

There must be *at least one queued vehicle at the start of the cycle*.

- **Criterion 1.a.1**

The distance from the front of the first vehicle in the subject cycle to the give-way / yield line at the time when the first circulating vehicle crosses the conflict line, L_{y1} satisfies:

$$L_{y1} \leq 15 \text{ m} / 50 \text{ ft}$$

where L_{y1} = distance from the front of the first vehicle in the cycle to the give-way/yield line.

When the previous cycle is not saturated, or it is saturated but it does not have a residual queue, the current cycle is considered to have a queued vehicle at the start of the cycle if *Criterion 1.a.2* is satisfied.

Figure 5.3 shows such a situation where a vehicle decelerates slowly at the start of the current cycle due to the opposing vehicles and then queues at the start of the next cycle. The vehicle is close enough to the give-way/yield line to be considered queued.

OR

- **Criterion 1.a.2**

There is at least one *residual queued vehicle* at the end of the *previous cycle* according to the *residual queued vehicle spacing*, L_{srp} that satisfies:

$$L_{srp} \leq 20 \text{ m} / 70 \text{ ft}$$

where L_{srp} is the saturation spacing between the last entering vehicle in the previous cycle and the first vehicle queuing at the start of the subject cycle at the time when the last entering vehicle crosses the give-way / yield line.

First queued vehicle in the second cycle in *Figure 5.3* is a residual queue.

AND

Condition 1.b

All vehicles entering after the first vehicle, including the last vehicle, in the subject cycle *must be queued*.

- **Criterion 1.b.1**

The spacing in front of the i th entering vehicle (including the last vehicle entering) in the subject cycle must satisfy a reasonable value of the saturation spacing, L_{si} corresponding to the saturation headway (t_f) and saturation speed (v_s), $L_s = v_s t_f$:

$$L_{si} \leq 20 \text{ m} / 70 \text{ ft for } i \geq 2$$

where L_{si} is the saturation spacing in front of the i th entering vehicle at the time when the previous entering queued vehicle ($i-1$) is crossing the give-way/line.

In *Figure 5.3*, saturation spacing in front of the *last queued vehicle entering* at the end of the subject cycle (4th vehicle) is shown as L_{sf} . This vehicle is further considered in *Criterion 1.b.2*.

AND

Condition 1.c

The subject cycle must be saturated.

○ **Criterion 1.c.1:**

There is at least one *residual queued vehicle* at the end of the *subject cycle* according to the *residual queued vehicle spacing*, L_{sr} that satisfies:

$$L_{sr} \leq 20 \text{ m / 70 ft and to } \leq 6.0 \text{ sec}$$

where L_{sr} is the saturation spacing between the last entering vehicle in the *subject cycle* and the first vehicle queuing at the start of the *next cycle* at the time when the last entering vehicle crosses the give-way / yield line, and t_0 is the unused part of the unblocked time, i.e. time from when the last entering vehicle in the subject cycle passes the yield line to the time when the first opposing (circulating) vehicle in the next cycle crosses the conflict line.

Criterion 1.a.2 is used to verify whether a residual queue exists at the start of a cycle, whereas *Criterion 1.c.1* determines whether a residual queue remains at the end of a cycle. Since the end of one cycle corresponds to the start of the next, if the *ith cycle* satisfies *Criterion 1.c.1*, then *Criterion 1.a.2* for the *(i+1)th cycle* is automatically satisfied.

OR

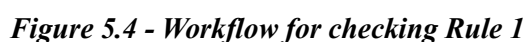
○ **Criterion 1.c.2:**

The *last entering queued vehicle* satisfies:

$$t_0 \leq 3.0 \text{ sec}$$

where t_0 is as above

Figure 5.4 depicts the workflow for checking if a cycle is reliable. It specifies all the conditions required to meet Rule 1 and all its criteria. As stated earlier, **Rules 2 to 4** are first applied by observation, prior to implementing the workflow. The labels in the figure are described below the workflow.



5.3 Statistics Obtained from Survey Using Reliable Gap Acceptance Cycles

The rules described in Section 5.2 were applied to each gap acceptance cycle observed on the Southbound (SB) and Eastbound (EB) approaches for the through and left lanes at the test site in order to filter out unreliable cycles. Considering the cycles with *passenger vehicles only* in the entry and circulating lanes, and *with no pedestrians*, the process yielded 136 and 82 reliable cycles for the SB and EB approaches, respectively (a total of 218 reliable cycles). The results for key parameters observed for reliable cycles are given in Tables 5.1a (separate data for SB and EB approaches) and Table 5.1b (SB and EB approaches combined). Table 5.1b also shows the parameters for contiguous and separate (non-contiguous) cycles (see Section 6.2.2). The results in Table 5.1b show that separate cycles can be used as reliable cycles.

Table 5.1a - Key parameters from observation of reliable gap acceptance cycles for Southbound and Eastbound approaches

Approaches		SB (Southbound) Pullen Rd	EB (Eastbound) Hillsborough St
Number of <i>All Cycles</i>		268	216
Number of Circulating/ Entering vehicles in <i>All Cycles</i>		699 / 461	589 / 419
Number of <i>Cycles</i> that met <i>Rules 2 to 4</i>		244	199
Number of <i>Reliable Cycles</i>		136	82
Percentage of <i>Reliable Cycles</i>		51%	38%
Number of Circulating / Entering vehicles in <i>Reliable Cycles</i>		295 / 201	185 / 135
Percentage of Circulating/ Entering vehicles in <i>Reliable Cycles</i>		42% / 43.6%	31% / 32.2%
Average circulating flow rate (pc/h)		758	706
Cycle time, c (sec)	Average	10.19	11.15
	Standard deviation	4.62	6.36
	Min - Max	3.46 - 24.48	3.80 - 31.87
Effective unblocked time, g (sec)	Average	4.12	4.27
	Standard deviation	2.69	2.63
	Min - Max	1.50 - 15.39	1.38 - 11.01
Effective blocked time, r (sec)	Average	6.07	6.88
	Standard deviation	3.92	5.88
	Min - Max	1.04 - 18.52	1.58 - 29.07
Follow-up headway, t _f (sec)	Average (1)	2.79	2.60
	Standard deviation	0.75	0.72
	Min - Max	1.50 - 6.05	1.38 - 5.84
Critical headway, t _c (sec)	Average (1)	4.19	4.47
	Standard deviation	1.27	1.18
	Min - Max	1.73 - 7.74	2.15 - 7.19
Ratio of follow-up headway to critical headway, t _f / t _c		0.67	0.58
Effective unblocked time ratio, u = g/c		0.404	0.383
Average saturation flow (intercept), s = 3600 / t _f (pc/h)		1290	1385
Average entry flow rate, q _e (pc/h)		406	372
Capacity, Q _g = s (g / c) (pc/h)		522	530
Average volume to capacity ratio x = q _e / Q _g		0.78	0.70

(1) Average values weighted by the number of entering vehicles

Table 5.1b - Key parameters from observation of reliable gap acceptance cycles for Southbound and Eastbound approaches combined

Approaches		SB and EB Combined		
		All Cycles	Contiguous cycles (2)	Separate cycles (2)
Number of <i>All Cycles</i>		484		
Number of Circulating/ Entering vehicles in <i>All Cycles</i>		1288 / 880		
Number of <i>Cycles</i> that met <i>Rules 2 to 4</i>		443		
Number of <i>Reliable Cycles</i>		218	190	28
Percentage of <i>Reliable Cycles</i>		45%	39%	6%
Number of Circulating / Entering vehicles in <i>Reliable Cycles</i>		480 / 336	420 / 295	60 / 41
Percentage of Circulating/ Entering vehicles in <i>Reliable Cycles</i>		37.3% / 38.2%	32.6 / 33.5	4.7% / 4.7%
Average circulating flow rate (pc/h)		739	726	774
Cycle time, c (sec)	Average	10.55	10.99	9.54
	Standard deviation	5.37	3.61	5.31
	Min - Max	3.46 - 31.87	5.82 - 24.36	3.80 - 28.99
Effective unblocked time, g (sec)	Average	4.18	4.30	3.92
	Standard deviation	2.67	1.59	2.28
	Min - Max	1.38 - 15.39	2.31 - 8.90	1.38 - 11.26
Effective blocked time, r (sec)	Average	6.37	6.69	5.62
	Standard deviation	4.78	3.23	5.19
	Min - Max	1.04 - 29.07	2.29 - 21.60	1.5 - 24.48
Follow-up headway, t_f (sec)	Average (1)	2.71	2.71	2.67
	Standard deviation	0.75	0.52	0.85
	Min - Max	1.38 - 6.05	2.02 - 4.40	1.38 - 5.67
Critical headway, t_c (sec)	Average (1)	4.30	4.52	4.03
	Standard deviation	1.24	0.81	1.07
	Min - Max	1.73 - 7.74	2.88 - 6.16	1.73 - 6.42
Ratio of follow-up headway to critical headway, t_f / t_c		0.63	0.60	0.66
Effective unblocked time ratio, $u = g/c$		0.396	0.391	0.411
Average saturation flow (intercept), $s = 3600 / t_f$ (pc/h)		1327	1330	1351
Average entry flow rate, q_e (pc/h)		389	389	389
Capacity, $Q_g = s (g / c)$ (pc/h)		526	520	555
Average volume to capacity ratio $x = q_e / Q_g$		0.74	0.75	0.70

(1) Average values weighted by the number of entering vehicles

(2) The average of multiple cycles used for calculating cycle time, effective blocked and unblocked times, follow-up headway and critical headway

As shown in *Table 5.1a*, the follow-up headway for the SB approach is slightly longer than that for the EB approach although its critical headway is shorter. Thus, the ratio t_f / t_c for SB and EB differ (0.67 and 0.58), but they are close to the generally accepted rule $t_f / t_c \approx 0.60$. The effective blocked time, unblocked time and the gap acceptance cycle time are longer on the EB lane although the effective unblocked time ratio, capacity and degree of saturation (v/c ratio) results are close.

For comparison with the gap acceptance survey results for the SB and EB approaches combined (Follow-up Headway, $t_f = 2.712$ s and Critical Headway, $t_c = 4.301$ s and the ratio $t_f / t_c = 0.63$ as seen in *Table 5.1b*), the *Sieglösch survey method* (Section 2.1) applied to the same data without including headways with zero departures gave $t_f = 2.772$ s and $t_c = 4.337$ s ($t_f / t_c = 0.64$). *Table 5.1b* also shows the differences between results for the contiguous and non-contiguous cycles.

5.3.1 Ratio of Entry Flow to Circulating Flow

Figure 5.5a shows the Ratio of Entry Flow to Circulating Flow using combined SB and EB approach data for Reliable Cycles including a trendline. This is of interest in relation to the modelling of unbalanced flow conditions. As expected, it is seen that the Ratio of Entering Flow to Circulating Flow values are high at low circulating flows and low at high circulating flows. Data observed at the subject roundabout did not include very high values of this ratio (highest value is 4.0) compared with the HCM roundabout research data where values well above 4.0 were observed [4].

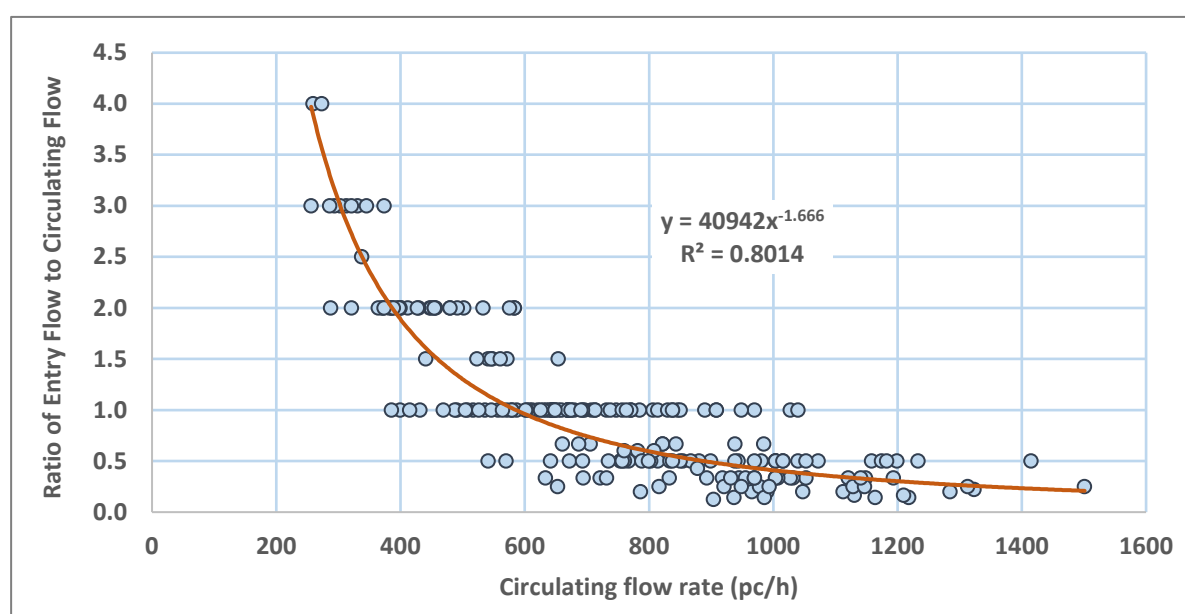


Figure 5.5 - Ratio of Entry Flow to Circulating Flow for Reliable Cycles

5.3.2 Sum of Entering Flow (Capacity) and Circulating Flow

The *sum of entering flow (capacity) and circulating flow* is often discussed by practitioners. *Figure 5.6* shows the values of this parameter when using the combined SB and EB approach data for Reliable Cycles including a trendline.

The figure shows that high values of the *sum of entering flow (capacity) and circulating flow* are achieved at high circulating flows. This may indicate a potential for higher entry flow values at low circulating flows. This comment relates to the modelling of unbalanced flow conditions.

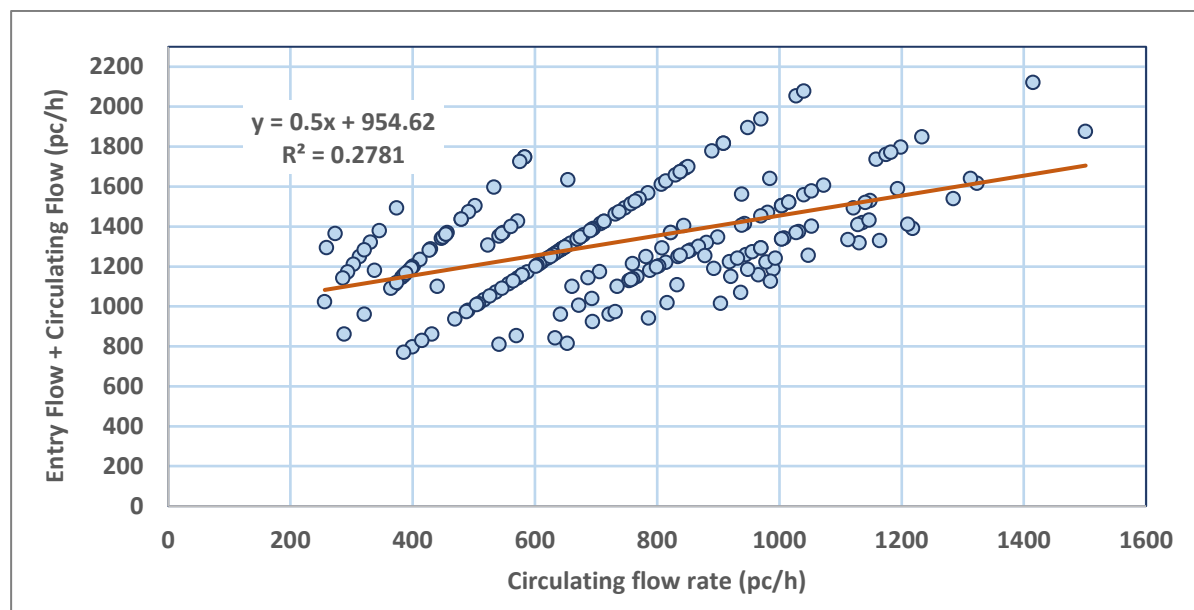


Figure 5.6 - The Sum of Entering Flow (Capacity) and Circulating Flow for Reliable Cycles

5.3.3 Follow-up Headway and Critical Headway Distributions

Figure 5.7 illustrates the empirical cumulative distribution functions (CDF) for the observed follow-up headways in orange colour and critical headways in red colour) and the CDF for the estimated critical headway distribution using the Maximum Likelihood Estimate (MLE) assumption of a lognormal distribution [8] is shown in blue. A Kolmogorov-Smirnov test assessed the validity of the critical headway distribution in the MLE method with a p-value of 0.76 for the SB lane and 0.62 for the EB lane. These results indicate that the two distributions are not different at a significance level of 0.05. Moreover, the estimated and observed average critical headways are close to each other, showing only a 0.1 second difference between them for both lanes.

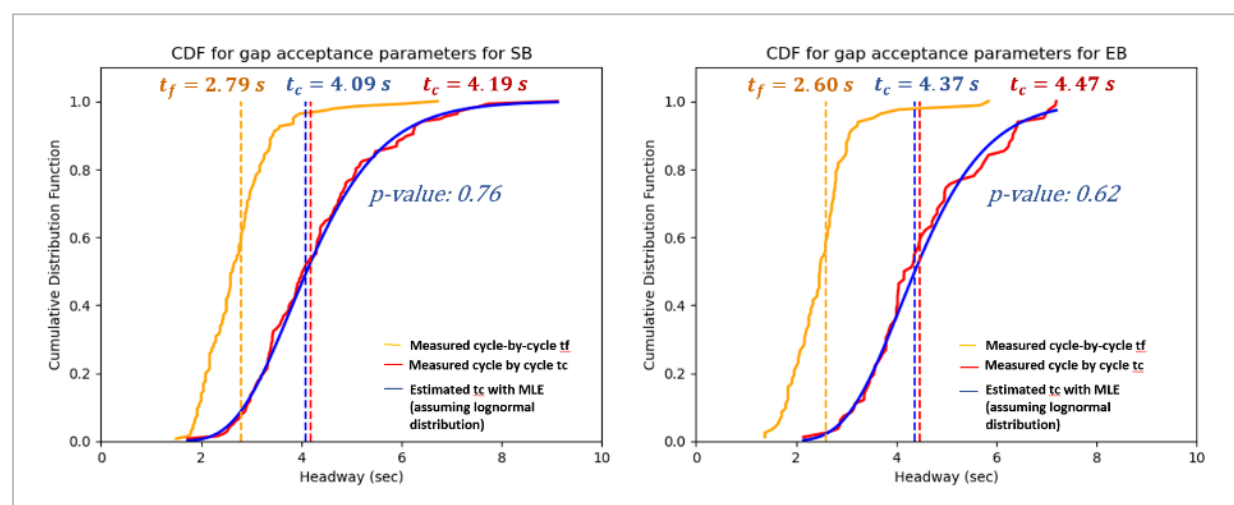


Figure 5.7 - Cycle-based Cumulative Distribution Functions for critical headways and follow-up headways for SB and EB lanes

5.3.4 Comparison of Observed and Estimated Effective Blocked and Unblocked Times

The parameters in Equations (3.2) to (3.4) for effective blocked time (r), effective unblocked time (g) and gap acceptance cycle time (c) vary depending on the chosen headway distribution model for the circulating vehicles. Figure 5.8 illustrates the average effective blocked time (red) and effective unblocked time (green) values estimated for SB and EB approaches using the M3D, M3B, M3T, M1 and M2 headway distribution models for circulating stream vehicles as well as the average values from field observations. These models differ with the assumption about the proportion of bunched vehicles in the circulating flow. The corresponding gap acceptance cycle time (c), effective unblocked time ratio ($u = g / c$) and gap acceptance capacity values are also given in Figure 5.8.

The model estimates shown in Figure 5.8 were calculated using the default bunching model parameters shown in Tables 3.1 and 3.2, and the average values of follow-up headway, critical headway and circulating flow rate given in Table 5.1a.

As seen in Figure 5.8, while the M3D and M3T bunching models tended to overestimate the effective unblocked time ratio and gap acceptance cycle time, the M3B and M2 models produced estimates close to the observed values for both SB and EB lanes. This finding indicates that a lower level of bunching exists in the circulating stream at the average circulating flow rate observed. Surveys of arrival headway distributions were not carried out at this roundabout. Future research is recommended on bunching models for circulating stream headway distributions at single lane and multilane roundabouts.

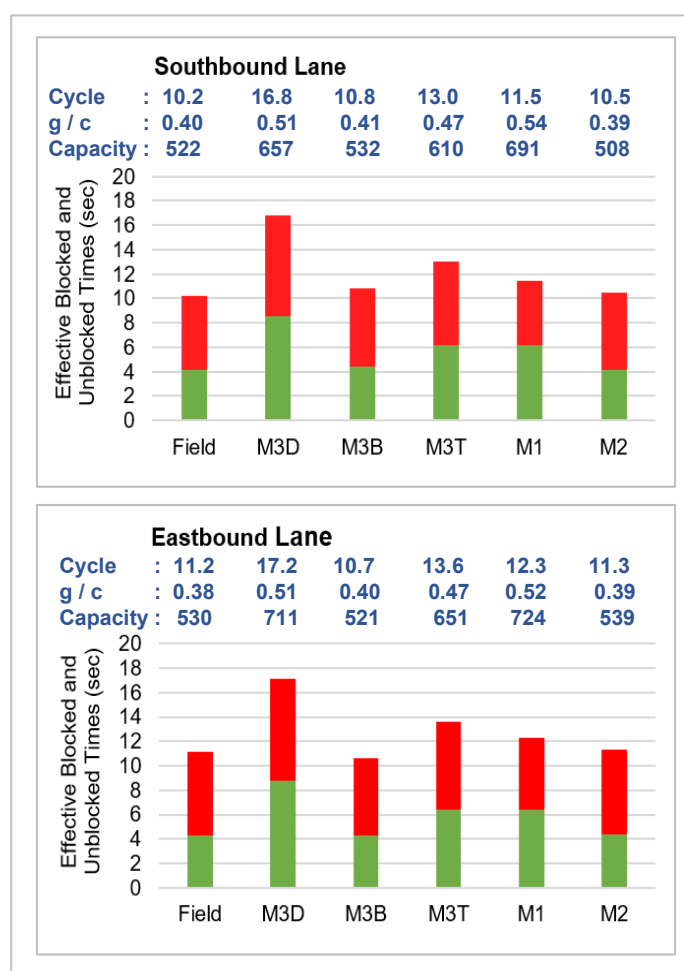


Figure 5.8 - Comparison of observed and estimated effective blocked and unblocked time values using average values of survey parameters at SB and EB lanes

5.3.5 Assessment of Capacity Models

Although the purpose of this research was to develop a survey method based on gap acceptance cycles using roundabout data, the findings of the research were assessed by applying some alternative roundabout capacity models to the gap acceptance cycle data.

Detailed results of the analyses are given in *Section 6*.

6. Capacity Analysis Results

This section presents the results of analyses to apply the findings of the research to alternative roundabout capacity models discussed in *Section 3* including HCM, Siegloch and Akçelik models. The purpose is to explore and demonstrate how similar analyses could be carried out in cases when larger amounts of data are available considering the limited amount of data in this study.

In *Sections 6.1 and 6.2*, capacity analysis results are presented using data for *SB and EB approaches combined*. *Section 6.1* presents the capacity analysis outcomes using *individual (disaggregate) cycle data* (218 reliable cycles as listed in *Table 5.1b* in *Section 5.3*). In *Section 6.2*, capacity analyses are carried out by applying *alternative data aggregation methods* which resulted in reduced number of data points.

The analyses presented include subjecting the capacity models to two fitting procedures:

- (i) using **Free (unconstrained best fit) regression**, and
- (ii) **Anchored regression** where the y-intercept is fixed to the value from the new survey method, a method used in order to mitigate the risk of unreliable capacity estimations stemming from data scarcity under low circulating flow conditions.

Anchored regression method is discussed in *Section 6.1.1*.

The roundabout capacity models used included the **HCM**, **Siegloch M1**, **Akçelik-M1**, **Akçelik-M2**, **Akçelik-M3D** and **Akçelik-M3B** models. All these models are based on the assumption of negative exponential headway distribution for circulating vehicles, but with different bunching assumptions (see *Tables 3.1 and 3.2* in *Section 3.3*).

Capacity analyses were also conducted for the *Southbound (SB) approach only* (136 reliable cycles as seen in *Table 5.1a* in *Section 5.3*). The analyses included using *individual cycle data* as in *Section 6.1* and *aggregate cycle data* as in *Section 6.2*. The capacity model comparisons using data for the SB approach only indicated a similar pattern to the results discussed in *Sections 6.1 and 6.2* for SB and EB approach data combined. The results for SB approach only are not included in this report.

6.1 Capacity Analyses Using Individual Cycle Data

This section presents the results of capacity analyses using *individual (disaggregate) cycle data* for the Southbound (SB) and Eastbound (EB) approach data combined.

The combined SB and EB dataset includes observations from 218 reliable cycles (see *Table 5.1b* in *Section 5.3*).

The roundabout capacity models **Siegloch M1**, **Akçelik-M1**, **Akçelik-M2**, **Akçelik-M3D** and **Akçelik-M3B** used for analyses were constructed from:

- (i) **Survey** results for the gap acceptance parameters *critical gap*, t_c and *follow-up headway*, t_f ,
- (ii) **Free (unconstrained best fit) regression** of capacity vs circulating flow, and
- (iii) **Anchored regression** with $3600 / t_f$ as the y-intercept.

These three methods are denoted as "Survey", "Free", and "Anchored", respectively.

6.1.1 Anchored Regression Method

The *Anchored regression* method helps to mitigate the risk of unreliable capacity estimations stemming from data scarcity under low circulating traffic conditions. This method was applied in deriving the HCM Edition 6 roundabout capacity model [1-4, 30].

Figure 6.1 shows the frequency of capacity data points for reliable cycles as a function of the circulating flow in 100 pcu/h intervals. Average values of entering flow (capacity) per 100 pcu/h interval are also shown in *Figure 6.1*.



Figure 6.1 - Frequency of capacity data points as a function of the circulating flow and average entering flow (capacity) data in 100 pcu/h intervals

Detailed comparisons of the *Free regression* and *Anchored regression* methods for the HCM exponential model and UK linear capacity model [29-30] using the HCM Edition 6 roundabout capacity research data can be found in a report by Akçelik et al [4]. The report concluded that the exponential model capacity estimates using *Anchored regression* were close to the *Free regression* estimates for medium to high circulating flows (indicated by small increases of 2.0% to 6.7% in RMSE values over the *Free regression* method).

6.1.2 Results of Capacity Analyses

Table 6.1 gives a summary of the results including statistical metrics (t_f / t_c , RMSE and Increase in RMSE compared with the *Free regression* parameters for the *Survey* and *Anchored regression* methods) for capacity models applied to **individual (disaggregate) gap acceptance cycle data for Southbound and Eastbound approaches combined**.

RMSE values were calculated from:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (y_i - \hat{y}_i)^2} \quad (6.1)$$

where y_i is the observed capacity in the i th individual or aggregated gap acceptance cycle, $\hat{y}_i$ is the estimated capacity, n is the number of observations, and the summation is for $i = 1$ to n .

Table 6.1 includes the values of **Increase in RMSE (%)** compared with RMSE for *Free regression* for capacity models (relevant to the *Survey* and *Anchored* cases). It is seen that the values are not consistent across models. High values are noted for Siegloch-M1 and Akçelik-M1 models.

It is noted that the capacity models listed in Table 6.1 have very close R^2 values (range 0.271 - 0.292).

Table 6.1 - Key parameters and statistical measures for the subject capacity models for Southbound and Eastbound approaches combined using individual cycle data

Capacity Models for SB and EB approaches combined		t_r	t_c	Intercept (pc/h)	t_r / t_c	RMSE	Increase in RMSE of Free
HCM		2.609	4.976	1380	0.52	230.03	-
Siegloch-M1	Survey	2.712	4.301	1327	0.63	262.11	22.9%
	Free	3.336	5.172	1079	0.65	213.29	-
	Anchored	2.712	5.757	1327	0.47	213.68	0.2%
Akçelik-M1	Survey	2.712	4.301	1327	0.63	250.21	19.6%
	Free	3.331	4.543	1081	0.73	209.19	-
	Anchored	2.712	5.385	1327	0.50	213.43	2.0%
Akçelik-M2	Survey	2.712	4.301	1327	0.63	250.49	13.2%
	Free	3.465	3.465	1039	1.00	221.19	-
	Anchored	2.712	3.949	1327	0.69	244.46	10.5%
Akçelik-M3D	Survey	2.712	4.301	1327	0.63	240.67	13.9%
	Free	3.644	3.644	988	1.00	211.38	-
	Anchored	2.712	5.656	1327	0.48	216.31	2.3%
Akçelik-M3B	Survey	2.712	4.301	1327	0.63	227.52	6.7%
	Free	3.531	3.531	1019	1.00	213.13	-
	Anchored	2.712	4.187	1327	0.65	226.87	6.4%

Yellow cells indicate input values in regression.

Blue cells indicate **Increase in RMSE > 15%**

In the assessments for the *Survey* cases given in Table 6.1, the average critical gap and follow-up headway values found by the gap acceptance survey method were used as *fixed values in the gap acceptance capacity equations*. Unlike the corresponding models used in the SIDRA INTERSECTION software, the minimum capacity values at very high circulating flows were not applied, and no consideration was given to the effect of critical headway and follow-up headway values reducing with increased circulating flows, or to the effect of unbalanced flow conditions at high demand flow levels resulting in reductions in capacities [5, 6, 28, 31].

Figures 6.2a to 6.2d show the comparisons of the capacity model estimates for Siegloch-M1 and HCM models with the Akçelik-M1, Akçelik-M2, Akçelik-M3D and Akçelik-M3B models together with survey data for individual reliable cycles. Each figure includes the models calibrated using three regression methods: survey-based, free regression, and anchored regression. Comparisons of capacity models using the Anchored regression method are shown in Figure 6.3 for the HCM, Siegloch-M1, Akçelik-M1, Akçelik-M2, Akçelik-M3D and Akçelik-M3B models.

The results in Table 6.1 and Figure 6.2a show that the Siegloch-M1 and Akçelik-M1 models are close to each other when fitted using the same method (*Survey, Free regression, Anchored regression*). This alignment captures the shared exponential headway distribution assumption between these models.

As seen in other figures in this section, the Akçelik-M2 and Akçelik-M3B models estimate lower capacity values, especially at high circulating flows. This is due to the assumption of no bunching by the M2 model and no or low bunching by the Akçelik-M3B model as discussed above. Akçelik-M3D model capacity estimates are close to the M1 models for low to medium circulating flows but are closer to the M2 and Akçelik-M3B models for high circulating flows although it estimates high levels of bunching at high circulating flows.

As seen in Table 6.1 and Figures 6.2a to 6.2d, the *Free regression method* using individual cycles gave higher follow-up headway (low y-intercept) values for all models compared with the follow-up headway values from *Survey* (and used in *Anchored regression*). For the M2, M3 and M3B models this led to the follow-up headway / critical gap ratio, $t_f / t_c = 1.0$ because of the constraint $t_f / t_c \leq 1.0$ which applied in these cases.

As seen in Table 6.1 to 6.5, the *Free regression method* yielded the smallest Root Mean Square Error (RMSE) values for all capacity models as expected. While this method minimizes the error between predicted and observed values, the reliability of capacity estimates under low circulating flow conditions is compromised due to the scarcity of data points within that range as discussed in Section 6.1.1 in relation to the *Anchored regression* model. The issue about the t_f / t_c ratio is also indicative of this bias.

It should also be noted that the R-squared value no longer represents the proportion of variance in the dependent variable explained by the model, when comparing capacity models using the *Anchored regression* method. Rather, it reflects the strength of the correlation between the independent and dependent variables, taking into account the fact that the model is forced to pass through the origin.

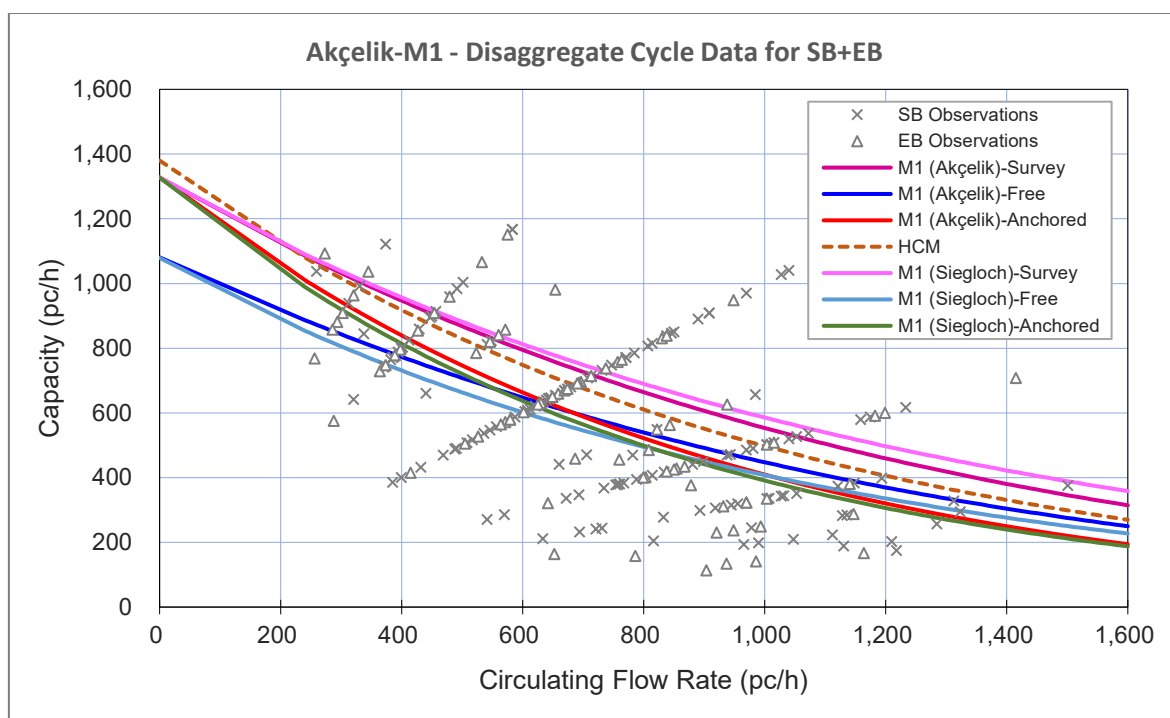


Figure 6.2a - Capacity model comparison between HCM, Siegloch-M1 and Akçelik-M1 models for combined Southbound and Eastbound approach data (individual cycles)

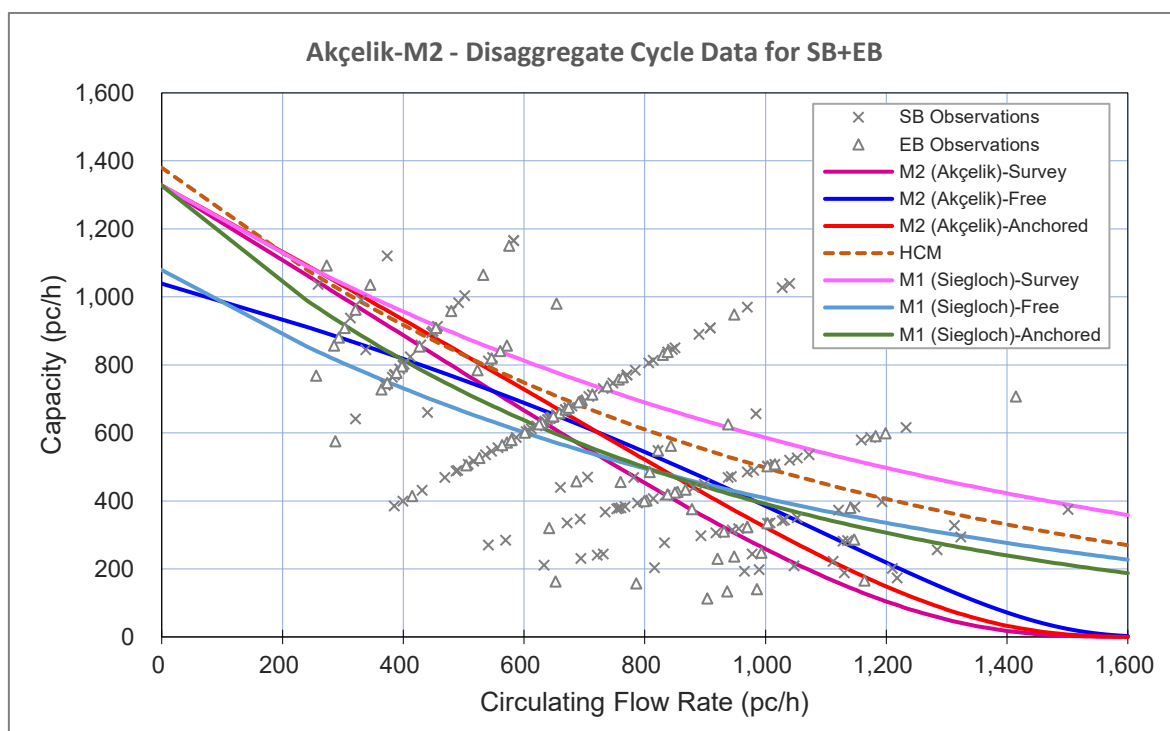


Figure 6.2b - Capacity model comparison between HCM, Siegloch-M1 and Akçelik-M2 models for combined Southbound and Eastbound approach data (individual cycles)

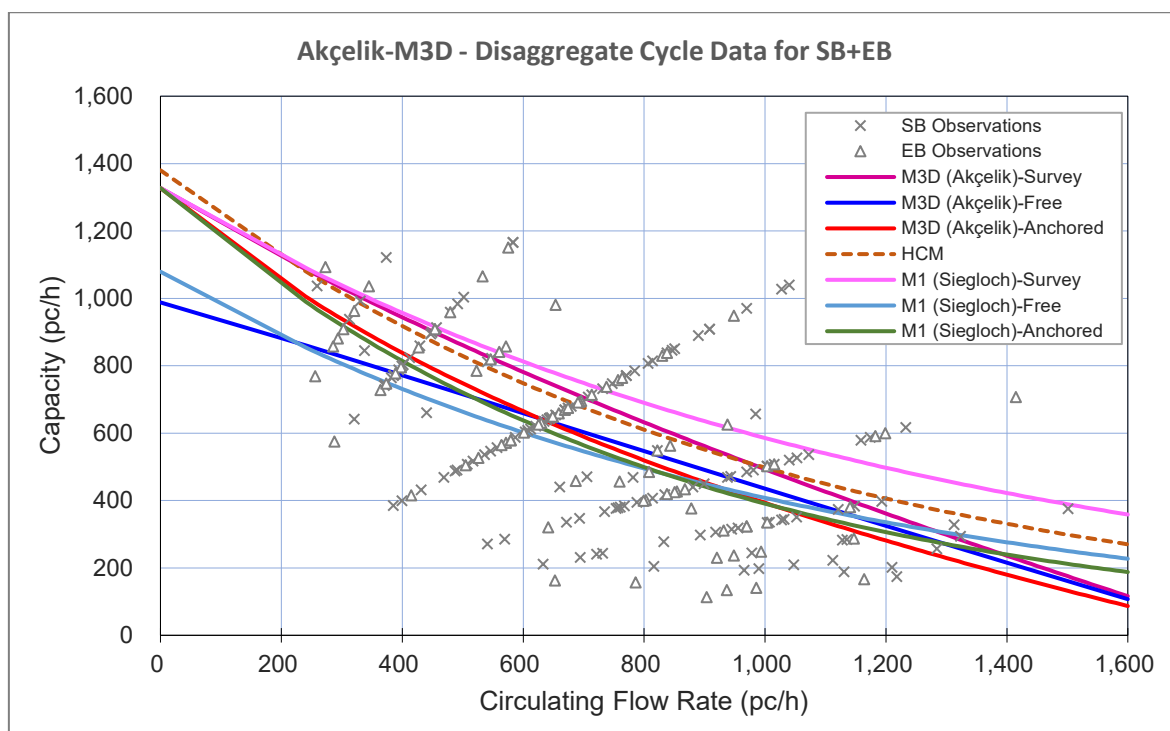


Figure 6.2c- Capacity model comparison between HCM, Siegloch-M1 and Akçelik-M3D models for combined Southbound and Eastbound approach data (individual cycles)

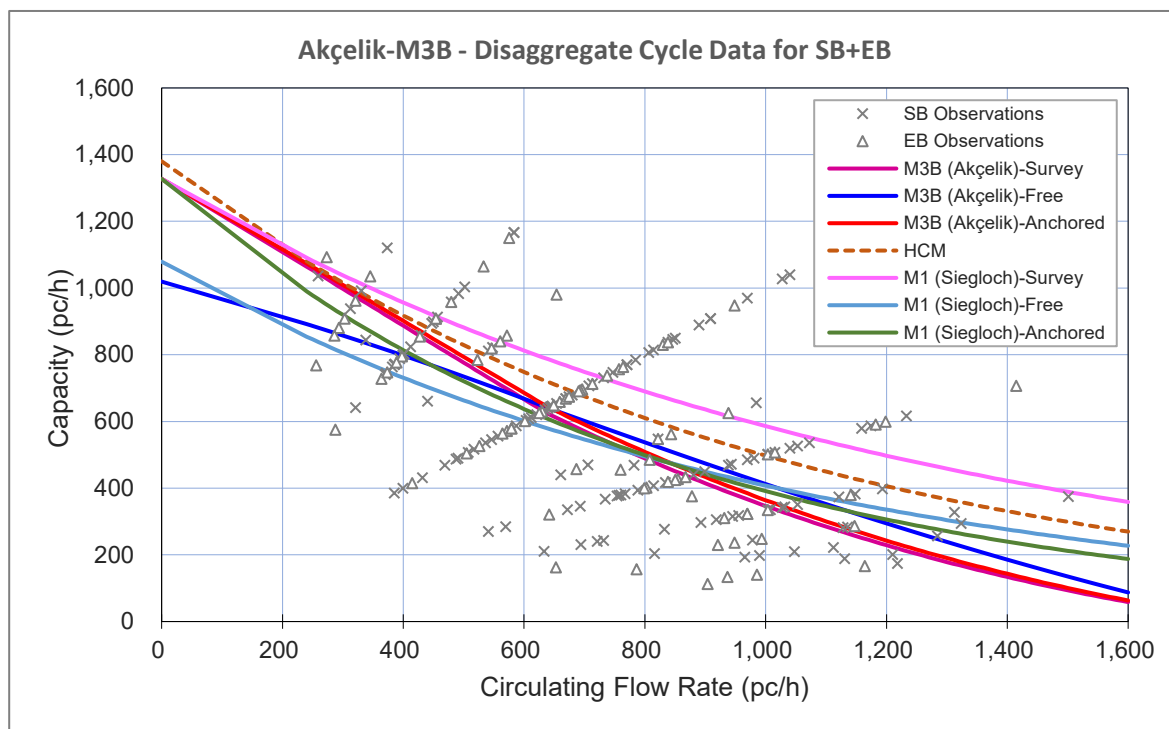


Figure 6.2d- Capacity model comparison between HCM, Siegloch-M1 and Akçelik-M3B models for combined Southbound and Eastbound approach data (individual cycles)

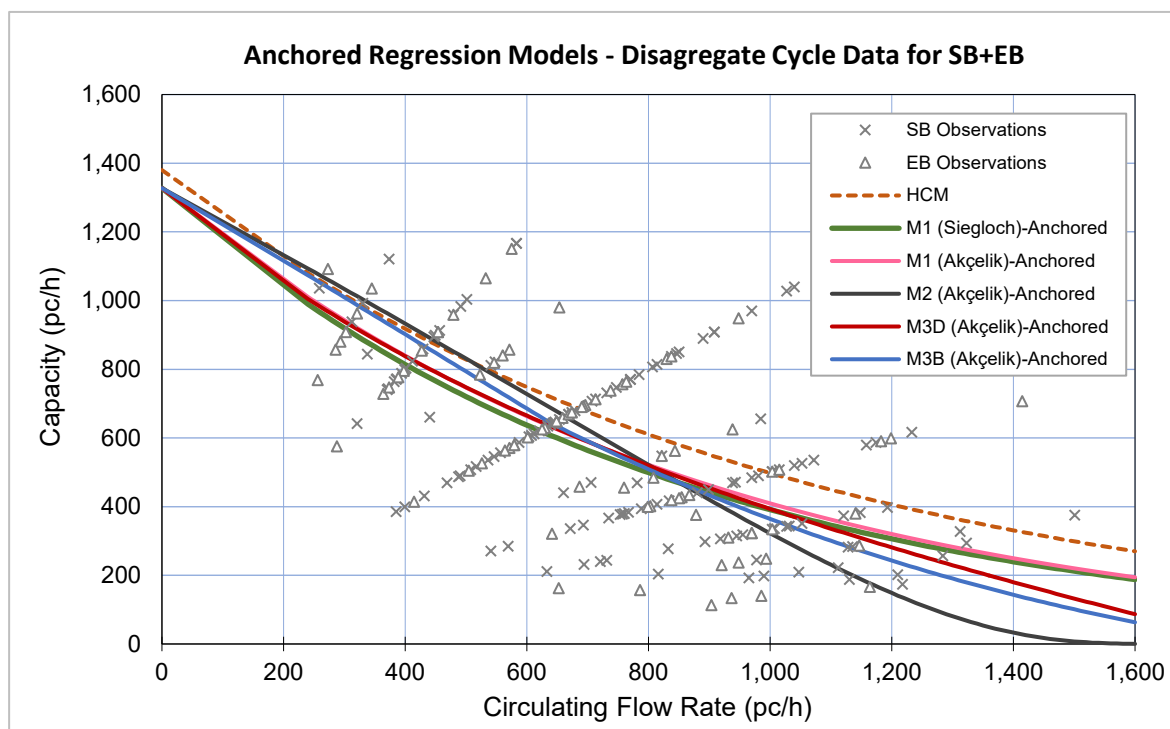


Figure 6.3 – HCM, Siegloch-M1, Akçelik-M1, M2, M3D and M3B roundabout capacity models using Anchored regression method for combined SB and EB approach data (individual cycles)

6.2 Capacity Analyses Using Aggregated Data

This section presents the results of capacity analyses using *aggregated cycle data* for the Southbound (SB) and Eastbound (EB) approach data combined.

Section 6.2.1 discusses the multiple linear patterns exhibited by the disaggregate gap acceptance cycle data points. The effect of eliminating this condition on capacity estimates was investigated using **two alternative data aggregation methods**:

- (i) combining *contiguous reliable cycles* and
- (ii) aggregating across *all cycles that have the same n_e / n_c ratio*.

The results of capacity analyses using these two methods are given in Sections 6.2.2 and 6.2.3.

6.2.1 Linear Patterns in Disaggregate Gap Acceptance Cycle Data

The disaggregate gap acceptance cycle data points in Figures 6.2a to 6.2d and Figure 6.3 in Section 6.1 are seen to form multiple linear patterns. This is because the ratio of capacity to circulating flow rate, Q_g / q_c in each *reliable cycle* is identical to the ratio of the number of entering vehicles to the number of circulating vehicles, n_e / n_c in that cycle. This can be explained as follows (see Figure 3.1 for the relationship between t_f and g):

$$Q_{gi} = (3600 / t_{fi}) (g_i / c_i) \quad (6.2)$$

$$q_{ci} = 3600 n_{ci} / c_i \quad (6.3)$$

$$t_{fi} = g_i / n_{ei} \quad (6.4)$$

$$Q_{gi} / q_{ci} = g_i / (n_{ci} t_{fi}) = n_{ei} t_{fi} / (n_{ci} t_{fi}) = n_{ei} / n_{ci} \quad (6.5)$$

where, in the *ith cycle*

q_{ci} = circulating flow rate (pc/h),

n_{ci} = number of circulating vehicles counted,

n_{ei} = number of entering vehicles counted,

c_i = gap-acceptance cycle time (s)

Q_{gi} = gap acceptance capacity for the entry lane (pc/h),

t_{fi} = follow-up headway (s)

g_i / c_i = effective unblocked time ratio.

As a result, reliable cycles having the same number of circulating and entering vehicles, can be observed forming a line with slope = 1:1; if the number of entering vehicles is twice that of circulating vehicles in a cycle, the data points will be located on the line with slope = 2:1, and so on. However, these linear patterns are independent of the key gap acceptance parameters follow-up headway and critical headway as seen in Figure 6.4.

Because the linear patterns will tend to degrade any regression model fitness, two methods to aggregate reliable gap acceptance cycles were applied as discussed below.

Note that other methods to aggregate reliable gap acceptance cycles could also be investigated. For example, a selected number of consecutive reliable cycles (3, 5, 10) could be aggregated forming data points that consist of random combinations of contiguous and separate (non-contiguous) cycles (see Section 5.3). Such aggregation methods are recommended for investigation.

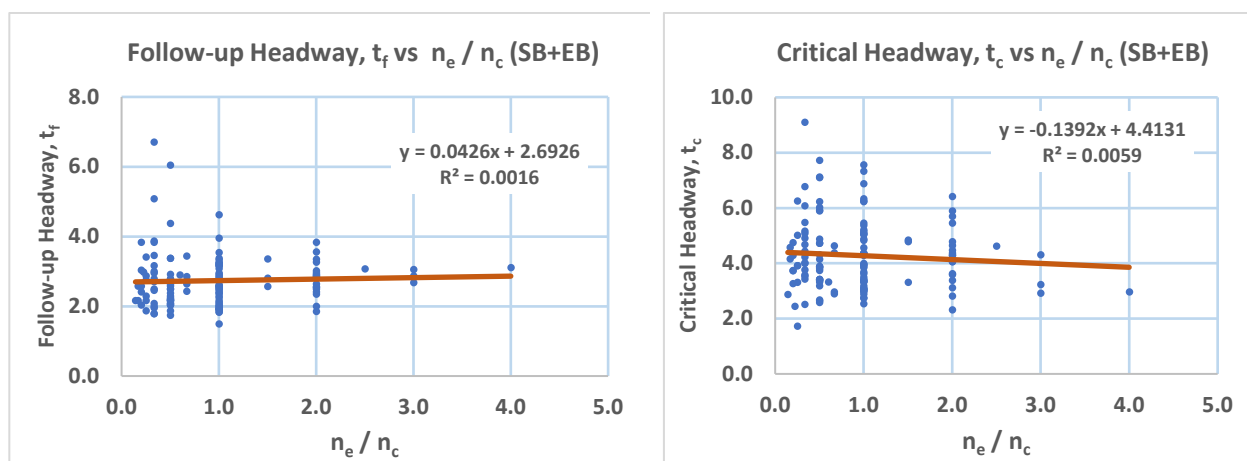


Figure 6.4 - Gap acceptance parameters Follow-up Headway and Critical Headway versus the ratio n_e / n_c

6.2.2 Data aggregated using contiguous reliable cycles

Table 6.2 provides a summary of the key parameters and statistical measures when applying the method to **aggregate data by combining contiguous reliable cycles** for *Southbound and Eastbound approaches combined*.

The corresponding capacity model comparisons for *Survey*, *Free regression* and *Anchored regression* methods are shown in Figures 6.5a to 6.5d. Figure 6.6 shows the comparisons between HCM, Siegloch-M1, Akçelik-M3D and Akçelik-M3B capacity models using *Anchored regression* method.

This aggregation method reduced the number of data points to a total of 76 (including 28 data points that remained as single reliable cycles) out of a total of 218 individual reliable gap acceptance cycle observations (see Table 5.1b). Thus, a residual linear pattern remained in the data due to the individual cycles that remain in the dataset.

The R^2 values increased slightly (range 0.312 - 0.341) compared with results for individual reliable cycles given in Table 6.1 (range 0.271 - 0.292).

As seen in Table 6.2 and Figures 6.5a to 5d, the *Free regression method* using aggregated contiguous cycle data gave higher follow-up headway (low y-intercept) values for all models compared with the follow-up headway values from *Survey* (and used in *Anchored regression*).

The comparison of results for *individual cycle data* and *aggregate contiguous cycle data* given in Table 6.3 show the following:

- (i) The method of *aggregation using contiguous reliable cycles* reduced the RMSE values for different capacity models in the range 9% to 20%. This was quite consistent across models.
- (ii) On the other hand, the changes in values of **Increase in RMSE (%)** compared with *RMSE for Free regression* were not consistent across models. These values decreased for Akçelik-M2 and Akçelik-M3B models while they increased for Siegloch-M1, Akçelik-M1 and Akçelik-M3D models.

It is not clear whether these trends would remain in the case of large datasets.

The results using data for the *SB approach only* had a similar pattern with the number of data points reduced to a total of 26. The results are not included in this report.

Table 6.2 - Key parameters and statistical measures for the subject capacity models for combined Southbound and Eastbound approaches using *aggregate contiguous cycle data* (includes a number of non-contiguous cycles)

Capacity Models for SB and EB approaches combined		t_f	t_c	Intercept (pc/h)	t_f / t_c	RMSE	Increase in RMSE cf Free
HCM		2.609	4.976	1380	0.52	196.73	-
Siegloch	Survey	2.712	4.301	1327	0.63	238.19	36.7%
	Free	2.896	5.341	1243	0.54	174.20	-
	Anchored	2.712	5.768	1327	0.47	175.66	0.8%
Akçelik-M1	Survey	2.712	4.301	1327	0.63	223.27	28.1%
	Free	2.969	5.059	1212	0.59	174.32	-
	Anchored	2.712	5.424	1327	0.50	174.90	0.3%
Akçelik-M2	Survey	2.712	4.301	1327	0.63	200.56	10.5%
	Free	3.509	3.509	1026	1.00	181.57	-
	Anchored	2.712	4.020	1327	0.67	194.93	7.4%
Akçelik-M3D	Survey	2.712	4.301	1327	0.63	209.19	18.7%
	Free	3.168	4.662	1136	0.68	176.25	-
	Anchored	2.712	5.686	1327	0.48	177.12	0.5%
Akçelik-M3B	Survey	2.712	4.301	1327	0.63	183.22	3.6%
	Free	3.540	3.572	1017	0.99	176.77	-
	Anchored	2.712	4.211	1327	0.64	182.66	3.3%

Yellow cells indicate input values in regression.

Blue cells indicate *Increase in RMSE > 15%*

Table 6.3 – Comparison of results for *individual cycle data* and *aggregate contiguous cycle data* for Southbound and Eastbound approaches combined

Capacity Models for SB+EB		RMSE	Increase in RMSE cf Free	RMSE	Increase in RMSE cf Free	Change in RMSE cf Individual
		Individual Cycles		Aggregated Cycles: Contiguous		
HCM		230.03		196.73	-	-14%
Siegloch	Survey	262.11	22.9%	238.19	36.7%	-9%
	Free	213.29	-	174.20	-	-18%
	Anchored	213.68	0.2%	175.66	0.8%	-18%
Akçelik-M1	Survey	250.21	19.6%	223.27	28.1%	-11%
	Free	209.19	-	174.32	-	-17%
	Anchored	213.43	2.0%	174.90	0.3%	-18%
Akçelik-M2	Survey	250.49	13.2%	200.56	10.5%	-20%
	Free	221.19	-	181.57	-	-18%
	Anchored	244.46	10.5%	194.93	7.4%	-20%
Akçelik-M3D	Survey	240.67	13.9%	209.19	18.7%	-13%
	Free	211.38	-	176.25	-	-17%
	Anchored	216.31	2.3%	177.12	0.5%	-18%
Akçelik-M3B	Survey	227.52	6.7%	183.22	3.6%	-19%
	Free	213.13	-	176.77	-	-17%
	Anchored	226.87	6.4%	182.66	3.3%	-19%

Blue cells indicate *Increase in RMSE > 15%*

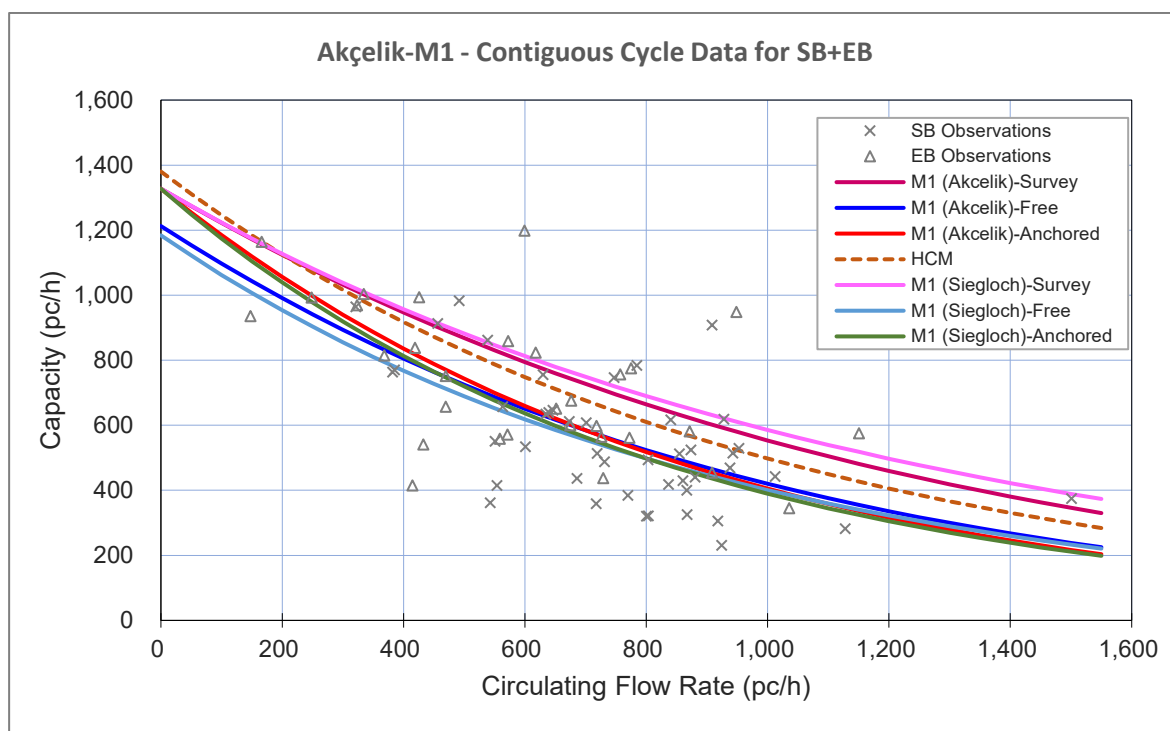


Figure 6.5a - Capacity model comparison between HCM, Siegloch-M1 and Akcelik-M1 models fitted to contiguous cycle data for combined Southbound and Eastbound approaches

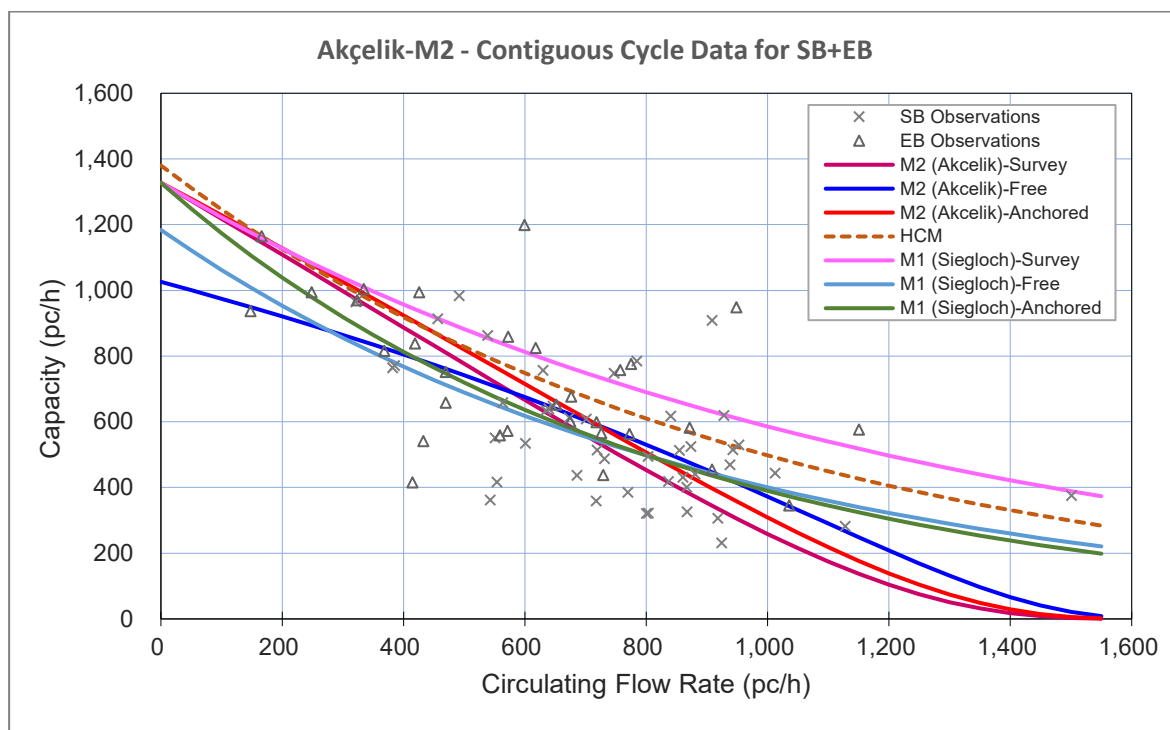


Figure 6.5b - Capacity model comparison between HCM, Siegloch-M1 and Akcelik-M2 models fitted to contiguous cycle data for combined Southbound and Eastbound approaches

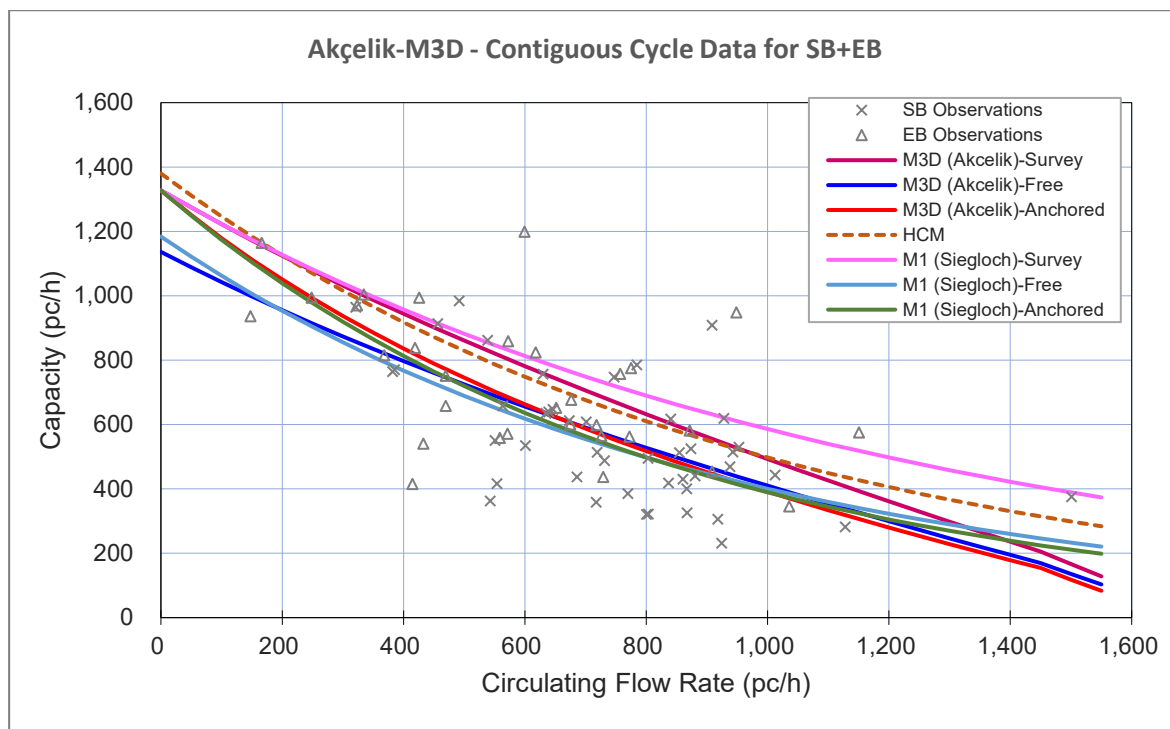


Figure 6.5c - Capacity model comparison between HCM, Siegloch-M1 and Akcelik-M3D models fitted to contiguous cycle data for combined Southbound and Eastbound approaches

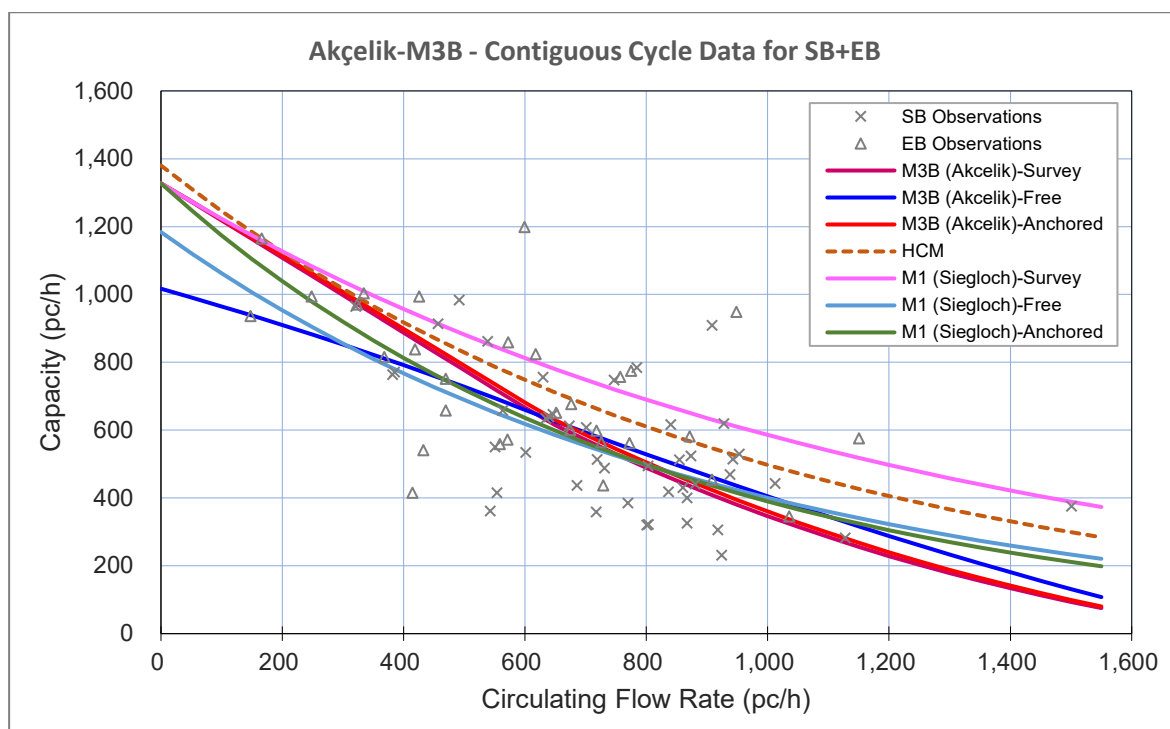


Figure 6.5d - Capacity model comparison between HCM, Siegloch-M1 and Akcelik-M3B models fitted to contiguous cycle data for combined Southbound and Eastbound approaches

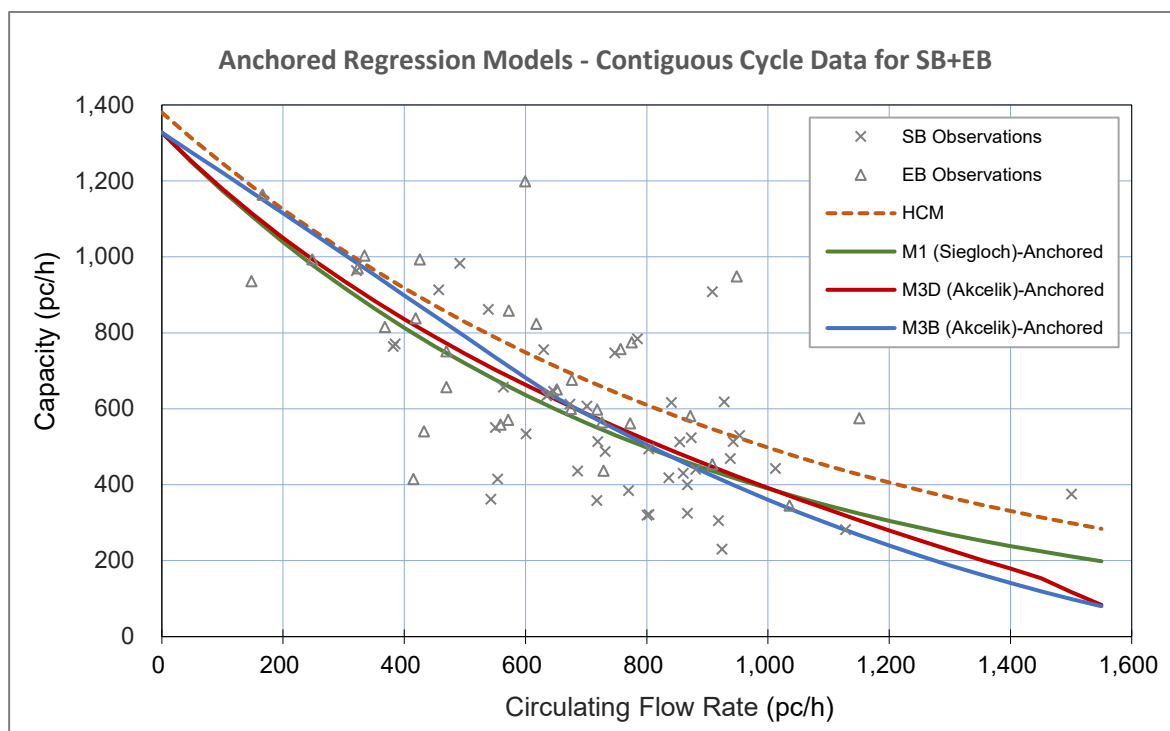


Figure 6.6 - Capacity model comparison between HCM, Siegloch-M1, Akcelik-M3D and Akcelik-M3B models with Anchored regression method for combined Southbound and Eastbound approach data (contiguous cycles)

6.2.3 Data aggregated using all cycles that have identical n_e / n_c

Table 6.4 provides a summary of the key parameters and statistical measures when applying the method to **aggregate data with identical n_e / n_c ratios** for **Southbound and Eastbound approaches combined**.

The corresponding capacity model comparisons for *Survey*, *Free regression* and *Anchored regression* methods are shown in *Figures 6.8a to 6.8d*.

This aggregation method reduced the number of data points to a total of 45 out of a total of 218 individual reliable gap acceptance cycle observations.

The R^2 values increased significantly (range 0.814 - 0.836) compared with results for individual reliable cycles given in *Table 6.1* (range 0.271 - 0.292).

As seen in *Table 6.4* and *Figures 6.8a to 8d*, Siegloch-M1, Akçelik-M1 and Akçelik-M3D capacity models using the *Free regression* method gave low follow-up headway (high y-intercept) values as well as large critical gap values resulting in very low t_f / t_c ratios. This is in contrast with the results using the individual cycles as discussed in *Section 6.1.1* as well as the results using aggregated contiguous cycle data discussed in *Section 6.2.2*. The t_f / t_c ratios remained low for *Anchored regression* for these models.

The comparison of results for *individual cycle data* and *aggregate cycle data grouped by n_e / n_c* given in *Table 6.5* show the following:

- (i) The method of *aggregating reliable cycles with identical n_e / n_c ratios* reduced the RMSE values for different capacity models in the range 9% to 50% with the exception of Siegloch-M1 model which had an increase of 4%. The results varied across models.
- (ii) On the other hand, the changes in values of **Increase in RMSE (%)** compared with *RMSE for Free regression* were not consistent across models. These values decreased for Akçelik-M2 and Akçelik-M3B models while they increased for Siegloch-M1, Akçelik-M1 and Akçelik-M3D models. However, the value for the case of Akçelik-M3B model for *Survey* had a slight increase.

It is not clear whether these trends would remain in the case of large datasets.

The results using data for the *SB approach only* had a similar pattern with the number of data points reduced to a total of 19. The results are not included in this report.

Table 6.4 - Key parameters and statistical measures for the subject capacity models for combined Southbound and Eastbound approaches using *aggregate cycle data grouped by n_e/n_c*

Capacity Models for SB and EB approaches combined		t_f	t_c	Intercept (pc/h)	t_f / t_c	RMSE	Increase in RMSE cf Free
HCM		2.609	4.976	1380	0.52	209.15	-
Sieglösch	Survey	2.712	4.301	1327	0.63	271.83	107.5%
	Free	2.156	7.644	1670	0.28	130.98	-
	Anchored	2.712	6.998	1327	0.39	147.41	12.5%
Akçelik-M1	Survey	2.712	4.301	1327	0.63	248.71	96.3%
	Free	2.299	6.886	1566	0.33	126.73	-
	Anchored	2.712	6.152	1327	0.44	133.76	5.6%
Akçelik-M2	Survey	2.712	4.301	1327	0.63	125.74	2.0%
	Free	2.926	4.156	1230	0.70	123.22	-
	Anchored	2.712	4.326	1327	0.63	125.68	2.0%
Akçelik-M3D	Survey	2.712	4.301	1327	0.63	210.63	64.9%
	Free	2.197	8.130	1638	0.27	127.73	-
	Anchored	2.712	6.556	1327	0.41	134.51	5.3%
Akçelik-M3B	Survey	2.712	4.301	1327	0.63	131.87	7.4%
	Free	2.729	4.637	1319	0.59	122.74	-
	Anchored	2.712	4.655	1327	0.58	122.75	0.0%

Yellow cells indicate input values in regression.

Blue cells indicate **Increase in RMSE > 15%**

Table 6.5 – Comparison of results for individual cycle data and aggregate cycle data grouped by n_e / n_c for Southbound and Eastbound approaches combined

Capacity Models for SB and EB approaches combined		RMSE	Increase in RMSE cf Free	RMSE	Increase in RMSE cf Free	Change in RMSE cf Individual
		Individual Cycles		Aggregated Cycles: grouped by n_e / n_c		
HCM		230.03		209.15		-9%
Siegloch	Survey	262.11	22.9%	271.83	107.5%	4%
	Free	213.29	-	130.98	-	-39%
	Anchored	213.68	0.2%	147.41	12.5%	-31%
Akçelik-M1	Survey	250.21	19.6%	248.71	96.3%	-1%
	Free	209.19	-	126.73	-	-39%
	Anchored	213.43	2.0%	133.76	5.6%	-37%
Akçelik-M2	Survey	250.49	13.2%	125.74	2.0%	-50%
	Free	221.19	-	123.22	-	-44%
	Anchored	244.46	10.5%	125.68	2.0%	-49%
Akçelik-M3D	Survey	240.67	13.9%	210.63	64.9%	-12%
	Free	211.38	-	127.73	-	-40%
	Anchored	216.31	2.3%	134.51	5.3%	-38%
Akçelik-M3B	Survey	227.52	6.7%	131.87	7.4%	-42%
	Free	213.13	-	122.74	-	-42%
	Anchored	226.87	6.4%	122.75	0.0%	-46%

Blue cells indicate *Increase in RMSE > 15%*

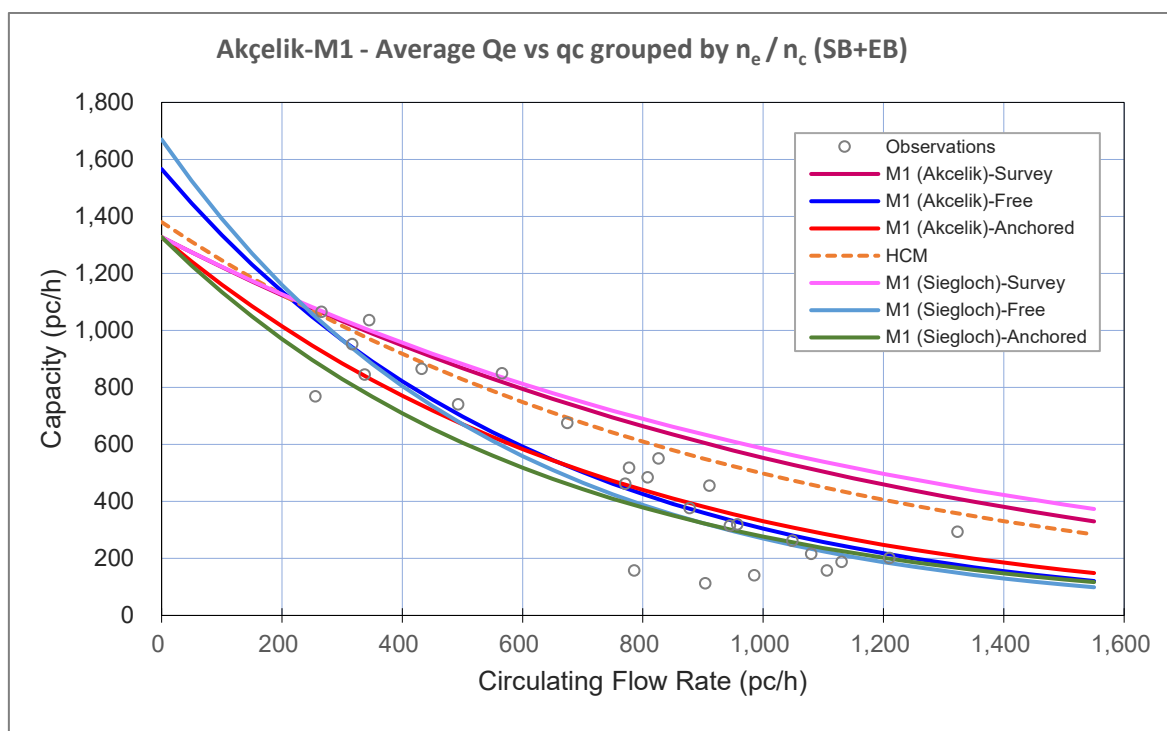


Figure 6.7a - Capacity model comparison between HCM, Siegloch-M1 and Akçelik-M1 models fitted to average of cycle-based observations grouped by n_e / n_c for or combined Southbound and Eastbound approaches

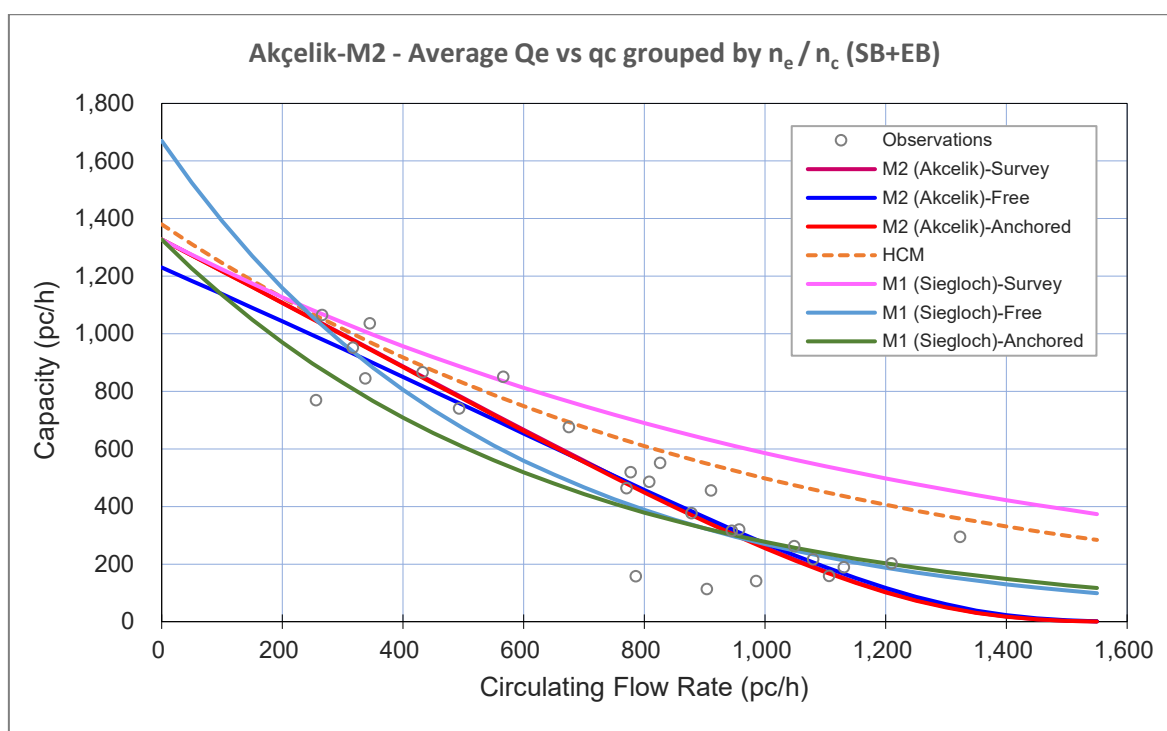


Figure 6.7b - Capacity model comparison between HCM, Siegloch-M1 and Akçelik-M2 models fitted to average of cycle-based observations grouped by n_e / n_c for or combined Southbound and Eastbound approaches

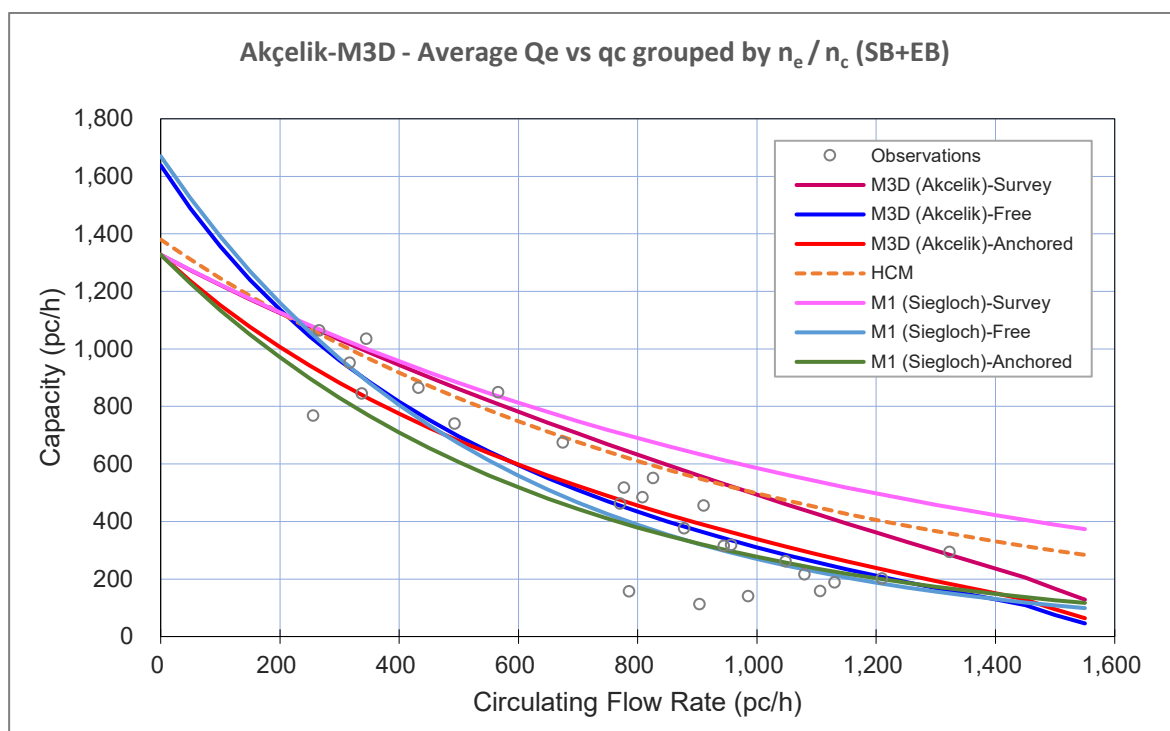


Figure 6.7c - Capacity model comparison between HCM, Siegloch-M1 and Akcelik-M3D models fitted to average of cycle-based observations grouped by n_e / n_c for combined Southbound and Eastbound approaches

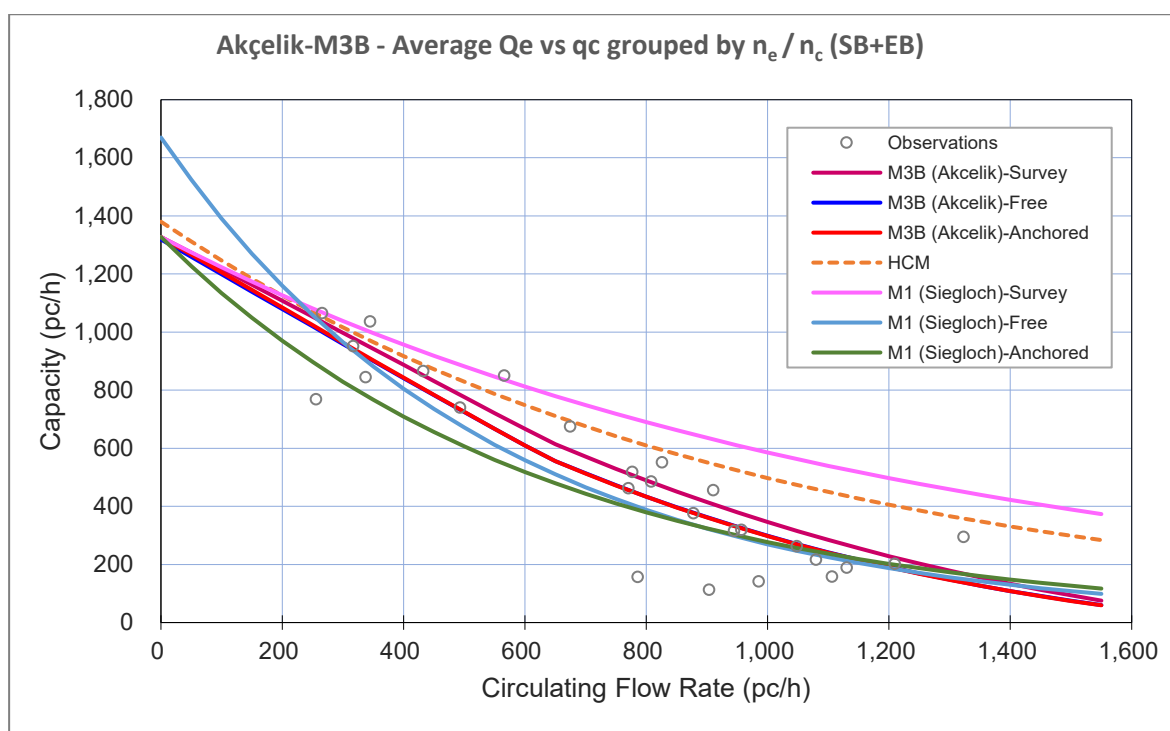


Figure 6.7d - Capacity model comparison between HCM, Siegloch-M1h and Akcelik-M3B models fitted to average of cycle-based observations grouped by n_e / n_c for combined Southbound and Eastbound approaches

6.3 Effect of Bunching in the Opposing Stream Headway Distribution Model

This section discusses the effect of *bunching* in the opposing (circulating) stream headway distribution model on capacity model results given in *Section 6*. The bunching models are described in *Section 3.3*.

Gap acceptance capacity estimation requires not only a model for estimation of *critical gap and follow-up headway* (t_f and t_c) parameters for *entering traffic* but also a model for estimating *bunching* in the headway distribution of *opposing traffic* (circulating stream for roundabouts).

Although not conclusive due to the limitations of the small dataset derived from the survey using the new gap acceptance survey method described in *Sections 4 and 5*, some findings of the capacity model comparisons summarised in *Section 6* may be explained according to the characteristics of the bunching model used:

- (i) The Siegloch-M1 and Akçelik-M1 capacity models did not perform well, probably due to the absence of bunching in these negative exponential models.
- (ii) Akçelik-M3D model did not perform well, probably because the high level of bunching estimated by this model using parameter $k_d = 2.2$ did not match the lower levels bunching at this roundabout.
- (iii) Akçelik-M3B model performed better probably because the bilinear bunched exponential model matched the lower levels bunching at this roundabout.

To test this proposition, the bunching models were calibrated by fitting them to circulating stream headway data observed in front of the Southbound (SB) and Eastbound (EB) approaches [33].

The calibration results are shown in *Table 6.6*. For the M3D (bunched exponential) model, *minimum (intra-bunch) headway*, Δ_c and *delay parameter*, k_d are calibrated. For the M3DS (shifted bunched exponential) model, the *limiting flow rate*, q_L is calibrated in addition to the Δ and k_d parameters.

RMSE in *Table 6.6* is calculated in accordance with *Equation 6.1* where y_i is the observed probability of headway less than t (sec) and $\hat{y}_i$ is the estimated probability of headway less than t (sec) (see Akçelik and Chung 1994).

As seen in *Table 6.6*:

- The *minimum headway* value estimated for the M3D and M3DS models, $\Delta = 1.9$ s is very close to the default value of $\Delta_c = 2.0$ s.
- For the M3D model with $\Delta_c = 2.0$ s fixed, the average *delay parameter* value estimated, $k_d = 0.57$ is much lower than the default value of $k_d = 2.2$ used for the capacity analyses given in *Sections 6.1 and 6.2*.
- For the M3DS model with $\Delta_c = 2.0$ s fixed, the average *delay parameter* value estimated, $k_d = 0.78$ is close to the value of $k_d = 1.0$ which corresponds to the M3B model used for the capacity analyses given in *Sections 6.1 and 6.2*. However, the value of the *limiting flow rate*, $q_L = 166$ pc/h is lower than the value used in the M3B model ($q_L = 641$ pc/h).

Circulating stream headway cumulative distributions for the Eastbound approach used for calibration of bunched exponential model M3D and shifted bunched exponential model M3DS are shown in *Figures 6.8a and 6.8b*. It is seen that the two calibrated models are very similar, also as shown in *Figure 6.9*.

Figure 6.9 shows a comparison of the estimates of *proportion unbunched* for different circulating flow headway distributions (M3T, M3B, M3D ($k_d = 2.2$), M3D ($k_d = 0.6$) and M3DS ($k_d = 0.8$, $q_L = 166$ pc/h)). These graphs were derived using the US HCM capacity model parameters for a single-lane roundabout ($t_f = 2.61$ s, $t_c = 4.98$ s) and the parameters shown in *Tables 3.1 and 3.2* (minimum proportion unbunched value is not applied).

It is seen that *bunching* estimates for the M3DS ($k_d = 0.8$ and $q_L = 166$ pc/h) and M3D ($k_d = 0.6$) models are very close.

Table 6.6 – Calibrated parameters of Bunched Exponential headway distribution models for combined Southbound and Eastbound approaches

Calibrated Bunching Model	Circulating Flow	Limiting Flow Rate	Minimum Headway	Delay Parameter	Proportion Free	Proportion Bunched	Error
	q_c (pc/h)	q_L (pc/h)	Δ_c	k_d	ϕ	$1 - \phi$	RMSE
M3D			<i>Estimated</i>				
Southbound (SB)	618		1.95	0.47	81%	19%	0.013
Eastbound (EB)	523		1.83	0.59	82%	18%	0.014
Average	571		1.89	0.53	82%	18%	
M3D ($\Delta_c = 2$)			<i>Given</i>				
Southbound (SB)	618		2.0	0.49	80%	20%	0.013
Eastbound (EB)	523		2.0	0.65	79%	21%	0.015
Average	571		2.0	0.57	79%	21%	
M3DS			<i>Estimated</i>				
Southbound (SB)	618	294	1.95	0.85	81%	19%	0.013
Eastbound (EB)	523	207	1.85	1.04	81%	19%	0.014
Average	571	251	1.90	0.94	81%	19%	
M3DS ($\Delta_c = 2$)			<i>Given</i>				
Southbound (SB)	618	193	2.0	0.68	80%	20%	0.013
Eastbound (EB)	523	139	2.0	0.88	79%	21%	0.015
Average	571	166	2.0	0.78	79%	21%	

The corresponding gap *acceptance capacity* graphs for the M3T, M3B, M3D ($k_d = 2.2$), M3D ($k_d = 0.6$) and M3DS ($k_d = 0.8$, $q_L = 166$ pc/h) models are very close as seen in *Figure 6.10*.

As in the case of *bunching* estimates, *gap acceptance capacity* estimates for the M3DS ($k_d = 0.8$ and $q_L = 166$ pc/h) and M3D ($k_d = 0.6$) models are seen to be very close.

Table 6.7 gives a summary of the results including statistical metrics (t_f / t_c , *RMSE* and *Increase in RMSE(%)*) for the *Survey* and *Anchored regression* methods compared with the *Free regression* method) for capacity models applied to *individual (disaggregate) gap acceptance cycle data* for *Southbound and Eastbound approaches combined*.

Figure 6.11 shows the Akçelik-M1, Akçelik-M2, Calibrated Akçelik-M3D and Calibrated Akçelik-M3DS capacity models using the *Anchored regression* method with individual cycle data for combined Southbound and Eastbound approach data.

Capacity analysis results given in *Sections 6.1 and 6.2* indicated that Models M2 and M3B with low levels of bunching in circulating flows performed better for this survey. For the M3D and M3DS capacity models with calibrated bunching models in *Table 6.7*, improvements are seen in the values of *Increase in RMSE (%)* as well as the *Critical Gap*, t_c (closeness to the values given by the *Survey* method). This confirms the low levels of bunching in circulating flows in this survey.

Table 6.7 - Key parameters and statistical measures for the subject capacity models for Southbound and Eastbound approaches combined using *individual cycle data*

Capacity Models for SB+EB		t_f	t_c	Intercept (pc/h)	t_f / t_c	RMSE	Increase in RMSE <i>cf Free</i>
Akçelik-M2	Survey	2.712	4.301	1327	0.63	250.49	13.2%
	Free	3.465	3.465	1039	1.00	221.19	-
	Anchored	2.712	3.949	1327	0.69	244.46	10.5%
Akçelik-M3B <i>Table 3.1</i> ($k_d = 1.0$, $q_L = 641$ pc/h)	Survey	2.712	4.301	1327	0.63	227.52	6.7%
	Free	3.531	3.531	1019	1.00	213.13	-
	Anchored	2.712	4.187	1327	0.65	226.87	6.4%
Akçelik-M3D <i>Default</i> ($k_d = 2.2$)	Survey	2.712	4.301	1327	0.63	240.67	13.9%
	Free	3.644	3.644	988	1.00	211.38	-
	Anchored	2.712	5.656	1327	0.48	216.31	2.3%
Akçelik-M3D <i>Calibrated</i> ($k_d = 0.6$)	Survey	2.712	4.301	1327	0.63	227.79	7.0%
	Free	3.572	3.572	1008	1.00	212.86	-
	Anchored	2.712	4.484	1327	0.60	226.65	6.5%
Akçelik-M3DS <i>Calibrated</i> ($k_d = 0.8$, $q_L = 166$ pc/h)	Survey	2.712	4.301	1327	0.63	225.98	6.4%
	Free	3.579	3.579	1006	1.00	212.45	-
	Anchored	2.712	4.528	1327	0.60	224.23	5.5%

Yellow cells indicate input values in regression.

Blue cells indicate *Increase in RMSE > 15%*

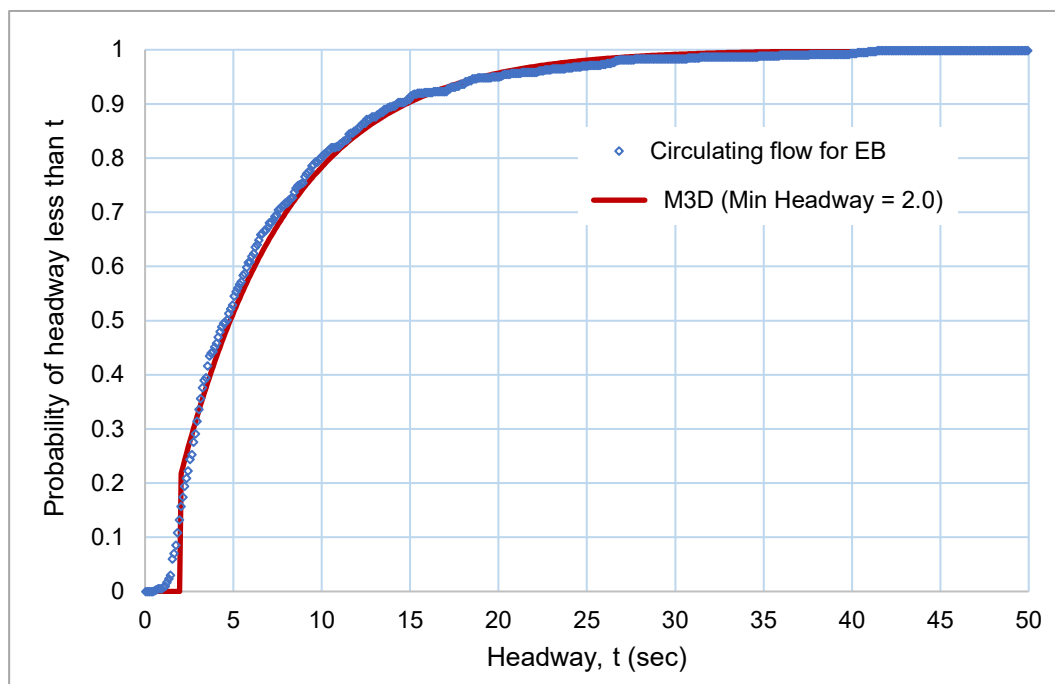


Figure 6.8a - Circulating stream headway cumulative distribution for Eastbound approach used for calibration of bunched exponential model M3D

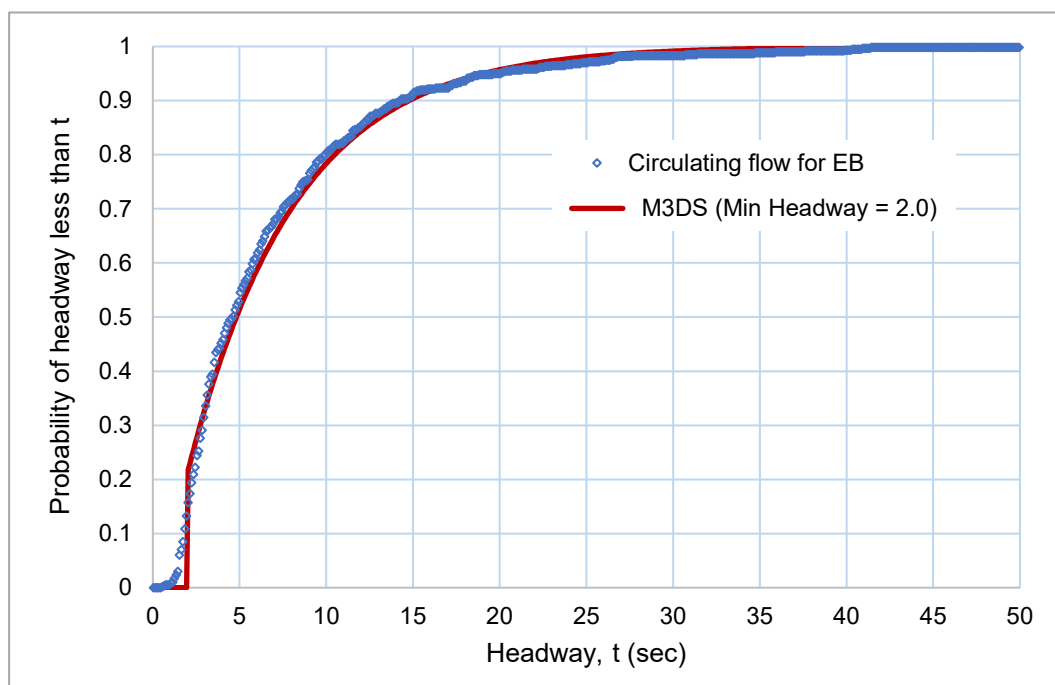


Figure 6.8b - Circulating stream headway cumulative distribution for Eastbound approach used for calibration of bunched exponential model M3DS

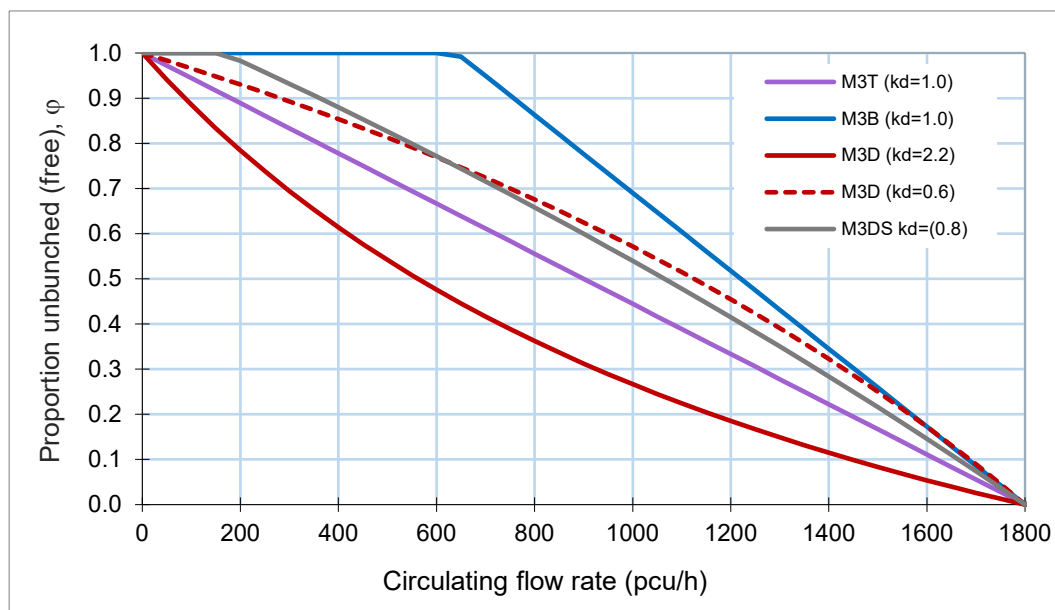


Figure 6.9 – Proportion unbunched (free) estimates from bunching models

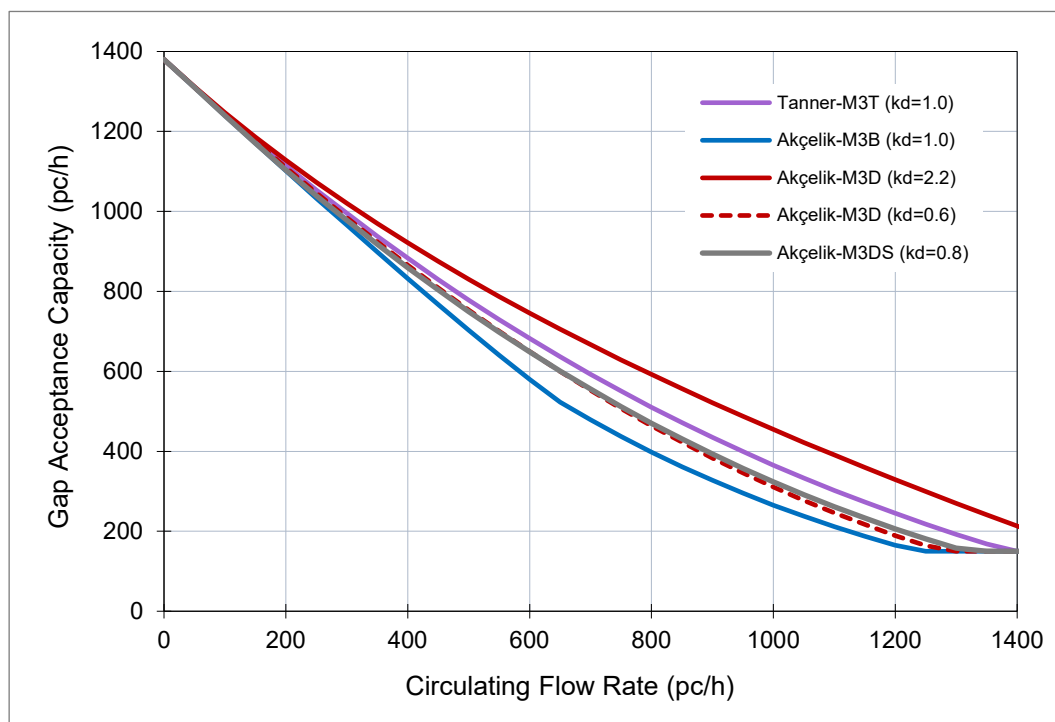


Figure 6.10 – Comparison of capacity estimates from bunched exponential models (minimum capacity of 150 pc/h applied)

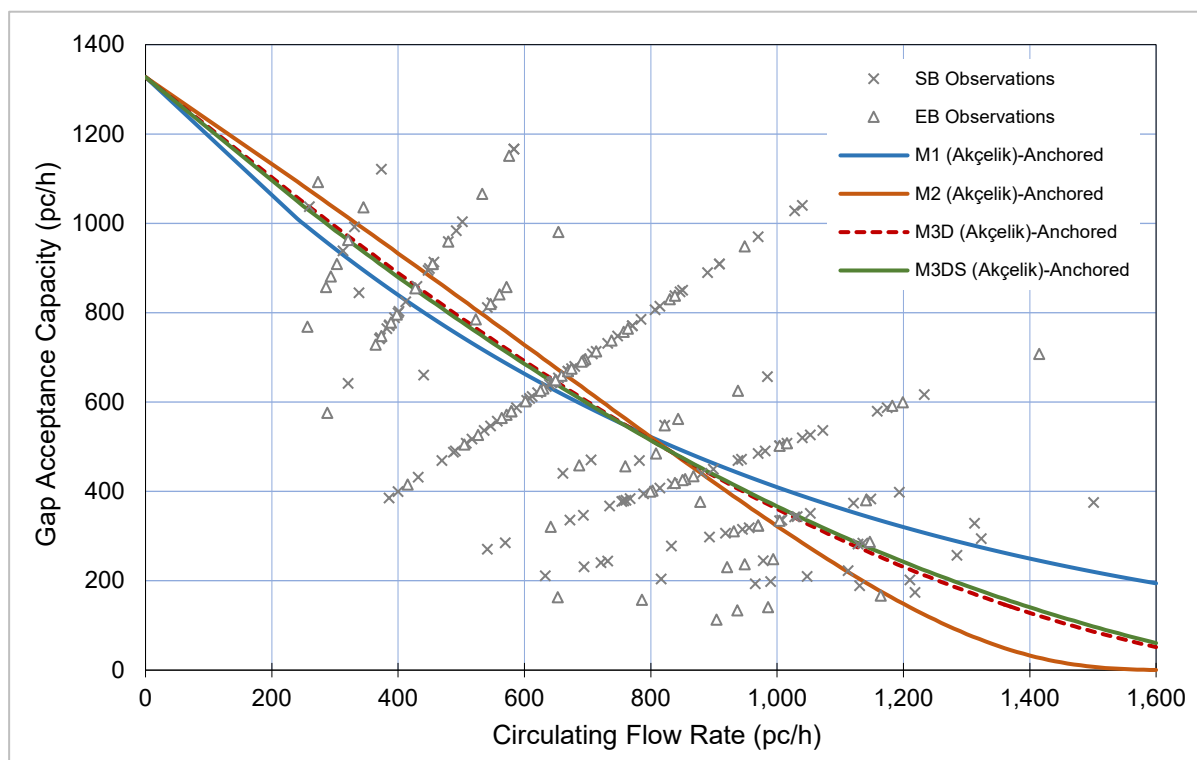


Figure 6.11 – Capacity model comparison between Akçelik-M1, Akçelik-M2, calibrated Akçelik-M3D and calibrated Akçelik-M3DS models for combined Southbound and Eastbound approach data (individual cycles)

7. Discussion

This study devised and applied a survey method aimed at measuring gap acceptance capacity as well as gap acceptance model parameters follow-up headway and critical gap simultaneously. This unique survey method is based on a previously developed theoretical method that use gap acceptance cycles derived from a traffic signal analogy approach which was used for gap acceptance capacity and performance estimation. The survey method was developed and assessed using real-world vehicle trajectory data at two approaches (SB and EB) of a single-lane roundabout with moderate traffic volume conditions in Raleigh, NC, USA.

Although the method was applied to a single-lane roundabout, it can be used for multi-lane roundabouts and other gap acceptance situations including unsignalised (stop and give-way / yield controlled) intersections, and permitted turns, turn on red and unsignalised slip / bypass lanes at signalised intersections, and various merge situations.

To apply this survey method with real-world observations, reliable gap acceptance cycles were clearly defined to meet specific rules and conditions. Trajectory data extracted from drone footage through video image processing techniques were used to generate data for the survey method. The approach enables the measurement of gap acceptance parameters cycle by cycle by observing saturated cycles which occur when all entry vehicles are queued.

The average observed values of gap acceptance parameters for entry vehicles on the SB and EB approaches were follow-up headways of 2.79 and 2.60 seconds, and critical gaps (headways) of 4.19 and 4.47 seconds, respectively. Using data combined for SB and EB approaches, follow-up headway and critical gap values of 2.71 and 4.30 seconds were observed, respectively. Compared to the follow-up headways, the critical headways exhibited larger standard deviations. The assumption of lognormal distribution for critical headway distributions cited in the literature was found to be statistically valid based on the empirical data. Moreover, the follow-up headway and critical headway values obtained from this survey method closely align with those derived using the well-known Siegloch method, demonstrating its reliability.

The observed average blocked time, unblocked time and gap acceptance cycle time values were compared with estimates obtained for M3D, M3B, M3T, M1 and M2 headway distribution models for circulating stream vehicles. These models differ in their assumption about the proportion of bunched vehicles in the circulating flow. Analyses of arrival headway distributions observed at this study site indicated a low proportion of bunched vehicles on the circulating road. Future research should explore bunching models for circulating stream headway distributions at both single-lane and multi-lane roundabouts.

Various gap acceptance capacity models, including the HCM default model, Siegloch-M1, Akçelik-M1, Akçelik M2, Akçelik M3D, and Akçelik M3B models, were evaluated using data from reliable cycles. Parameter estimation was performed using follow-up headway and critical gap values from the *Survey* method, *Free* (unconstrained best fit) regression method, and *Anchored regression* method.

A general issue affecting all roundabout survey methods is the low frequency of data points at both low and high circulating flow levels. This can introduce bias in capacity and performance model derivation based on real-world data. The *Anchored regression* method helps to mitigate the risk of unreliable capacity estimations stemming from data scarcity under low circulating traffic conditions.

Capacity model comparison results using individual cycle data and aggregate cycle data for the *SB approach only* indicated a similar pattern to the results discussed in *Section 6* for *SB and EB approach data combined*.

The results confirmed the validity of the new survey method, supporting the novel signal analogy concept with real-world data. The assessments comparing the performance of different gap acceptance capacity models were not conclusive as they were limited by the small size of the dataset available from this survey. The models estimating low levels of bunching in circulating flows performed better for this survey. Improvements in the performance of the calibrated M3D and M3DS models confirmed the low levels of bunching in circulating flows.

The observed cycle-based capacity and circulating flow rate patterns exhibited *multiple linear trends* which contributed to poor model fit. This was investigated by applying two cycle aggregation methods. Although these aggregation methods improved the model fit, the findings confirmed the need for large-scale survey datasets to ensure greater reliability.

Other methods to aggregate reliable gap acceptance cycles could be assessed, e.g. aggregation of a selected number of consecutive reliable cycle data (3, 5, 10) into data points that would consist of random combinations of contiguous and individual cycles.

It is noted that the capacity model assessments described in this report are restricted to the use of gap acceptance capacity models without involving more complicated aspects of capacity modelling of roundabouts as *interactive systems* (rather than treating as a series of T-intersections). Thus, the minimum capacity values at very high circulating flows were not applied, and no consideration was given to the effect of critical headway and follow-up headway values reducing with increased circulating flow rate, or to the effect of unbalanced flow conditions at high demand flow levels resulting in reductions in capacities [3, 28].

The Appendix shows how the new survey method can be used to determine gap acceptance factors for different vehicle classes in entry lanes.

Future research is recommended on assessing the various bunching models for opposing stream headway distributions, and the implementation of the new survey method including comparison of capacity models for gap acceptance situations at different traffic facilities.

8. Conclusions

Using real-world trajectory data, the results of this research validated the novel signal analogy concept used in developing gap acceptance capacity models and performance models which have been employed in the SIDRA INTERSECTION software. This new survey method allows measurement of follow-up and critical gap (headway) parameters and capacity of entry lanes *simultaneously* without requiring long periods of continuous queued vehicle departures typically required by traditional gap acceptance capacity survey methods. Thus, the new method based on observation of gap acceptance cycles allows the application of gap acceptance surveys at all levels of demand flows.

Future advancements should focus on the development of an *automated tool* for determination of reliable gap acceptance cycles, and also on enhancing the efficiency and accuracy of data analysis. Additionally, validating performance metrics such as delay, back of queue, and stops from each model against empirical observations is crucial. Extending the survey method to observe *important performance measures*, such as back of queue length, should also be considered.

While this study excluded cycles involving heavy vehicles and pedestrian effects due to insufficient data size, preliminary investigation of the inclusion of cycles with heavy vehicles indicated that the survey method can be used for determining *gap acceptance factors* for different vehicle classes in entry lanes for use in gap acceptance capacity model adjustments (see the Appendix).

Gap acceptance capacity estimation requires not only a model for estimation of critical gap and follow-up headway parameters for entering traffic but also a model for estimating *bunching* in the headway distribution of opposing traffic (circulating stream for roundabouts). Research on bunching in roundabout circulating streams is recommended.

Although the gap acceptance survey method described in this report was applied to a single-lane roundabout, it can be applied to *multi-lane roundabouts* and other gap acceptance situations including *unsignalised (stop and give-way / yield controlled) intersections*, and permitted turns, turn on red and unsignalised bypass lanes at *signalised intersections*, and various *merge* situations.

The use of the method for surveys at a larger number of road traffic facilities will allow for a more robust assessment of the utility of the method.

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APPENDIX – Estimation of Heavy Vehicle Gap Acceptance Factor

This appendix outlines the methodology employed to calculate the *Gap Acceptance Factor* for heavy vehicles at the subject roundabout. This parameter is used to adjust the two key gap acceptance parameters namely the follow-up and critical headways. As discussed in *Section 5.2*, the analysis discussed in the body of the report focused exclusively on reliable cycles that strictly included passenger cars / light vehicles on both the entry and circulating lanes. The analysis herein incorporates those reliable cycles where vehicles on the entry approach included both passenger cars and heavy vehicles.

Generally, heavy vehicles require a longer gap to enter the circulating lane compared to passenger car. Consequently, follow-up and critical headway observations in cycles involving heavy vehicles tend to be relatively longer. Thus, the effect of heavy vehicle entry on the key parameters was estimated by comparing the weighted average follow-up headway values between two scenarios:

- (i) using reliable cycles involving entering passenger cars only, and
- (ii) reliable cycles that included entering heavy vehicles.

Since there were no reliable cycles involving heavy vehicle entry on the Southbound approach, the *Gap Acceptance Factor* estimation below is limited to data from the Eastbound approach only. The parameters for both cases on the Eastbound approach are presented in *Table A.1*.

Table A.1 – Parameters used for the calculation of the Gap Acceptance Factor for heavy vehicles

	Cycles with Passenger Cars Only	Cycles with Mixed Passenger Cars and Heavy Vehicles
Number of Reliable Cycles	82	86
Number of all entering vehicles	135	140
Number of heavy entering vehicles	0	4
Heavy vehicle proportion (p_{HV})	0	0.029
Passenger car proportion ($p_{PC} = 1 - p_{HV}$)	1.0	0.971
Average t_f (weighted by # of entering vehicles)	$t_{fPC} = 2.59$	$t_{fMIX} = 2.67$
Average t_c (weighted by # of entering vehicles)	4.47	4.52
Ratio t_f / t_c	0.58	0.59

As shown in the table, the weighted average t_f and t_c increased by 0.072 and 0.042, respectively, after adding the observations involving the effect of heavy vehicles. Since the difference arose from the 2.9 % heavy vehicles, the *Gap Acceptance Factor* for heavy vehicles is derived as described below:

$$t_{fMIX} = p_{PC} t_{fPC} + p_{HV} t_{fHV} \quad (A.1)$$

$$t_{fHV} = (t_{fMIX} - p_{PC} t_{fPC}) / p_{HV} = f_{fHV} t_{fPC} \quad (A.2)$$

$$f_{fHV} = t_{fHV} / t_{fPC} = (t_{fMIX} / t_{fPC} - p_{PC}) / p_{HV} = f_{fHV} t_{fPC} \quad (A.3)$$

where

- f_{fHV} : *Gap Acceptance Factor* for heavy vehicles,
- t_{fMIX} : average follow-up headway for mixed passenger cars and heavy vehicles,
- t_{fPC} and t_{cPC} : average follow-up and critical headways with passenger cars only,
- t_{fHV} and t_{cHV} : average follow-up and critical headways for heavy vehicles only, and
- p_{PC} and p_{HV} : proportion of passenger cars and heavy vehicles, respectively.

Using the values from *Table A.1*:

- (i) *Gap Acceptance Factor* for heavy vehicles is found as $f_{HV} = (2.67 / 2.59 - 0.971) / 0.029 = 2.065$, and
- (ii) the follow-up headway for heavy vehicles is found as $t_{fHV} = 2.065 \times 2.59 = 2.67$ s.

Thus, in spite of the relatively small number of heavy vehicles used in this analysis, the estimated *Gap Acceptance Factor* value of 2.065 is a very reasonable value (e.g. default value of 2.0 in the US HCM).

Additional observations of heavy vehicle parameters as illustrated in this Appendix are highly needed, along with those for other key vehicle classes in future research.

