ESTIMATING DELAY AT ROUNDABOUTS

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Abstract

Models that estimate delay at unsignalized intersections allow analysts to compare the operational performance of various intersection configurations prior to implementation. A delay estimation model for single lane roundabout approaches has been developed and compared to delay measured in the field at single lane roundabouts in the U.S. Queuing theory was used to develop this model which is applicable under steady state conditions and with the assumption of an M/G/1 queuing regime. This model's performance is also compared to a similar queuing model developed previously. The delay estimation model developed as part of this study can be used along with the newly released HCM 2000 procedure for estimating capacity at single lane roundabout approaches to make more complete comparisons between roundabout, TWSC or AWSC operational performance.

ACKNOWLEDGEMENTS

INTRODUCTION

Roundabouts are being implemented throughout the United States in a variety of situations. Many states are considering roundabouts as a viable alternative to two-way stop controlled intersections (TWSC), all-way stop controlled intersections (AWSC), and in some cases signals and complex freeway interchanges. As a result of the increasing popularity of roundabouts in this country, the Highway Capacity and Quality of Service Committee included a procedure for estimating approach capacity at single lane roundabouts based on international experience and limited U.S. data. In addition, the Federal Highway Administration is set to release a design guide for roundabouts in the United States, entitled "Roundabouts: An Information Guide", that was developed by Kittelson & Associates along with an international panel of experts.

While the Highway Capacity Manual (HCM) 2000 (2000) includes a gap-acceptance based procedure for estimating capacity at single lane roundabouts, a delay model was not included in the most recent version of the HCM. This paper presents a delay estimation model along with a procedure for estimating queue length for single lane roundabout approaches based on probability theory. The model also includes a procedure for estimating service time and the variance of service time, where service time is defined as the time spent in the first position of the queue prior to entering the circulating stream. The model was developed from data collected at six single lane roundabouts located in the Untied States.

The following sections consist of a brief review of past models developed to estimate delay at unsignalized intersections; the study methodology; a comparison to field measurements and model estimates of delay; a worked example problem; and conclusions and recommendations section for future research.

2.0 STATE-OF-THE-ART REVIEW

Gap acceptance models for estimating delay experienced by drivers entering unsignalized intersections exist in many countries, including the United States and Australia. Single-lane roundabouts are similar to TWSC intersections in that there are assigned priority and non-priority

traffic streams. In both intersection types, a driver on the minor approach must scan the major traffic stream for an acceptable gap before entering the priority traffic stream. Gap acceptance theory accounts for three characteristics of the interacting streams, namely:

Availability of gaps in the conflicting or circulating stream (headway distribution)

Usefulness of these gaps to entering drivers (required gap of entering drivers)

Rate that drivers follow each other into larger gaps (know as follow-up time)

Troutbeck (1989) modeled headway characteristics in the circulating stream of a roundabout via the Cowan M3 distribution. The Cowan M3 distribution focuses on modeling the proportion of platooned and non-platooned vehicles in the circulating stream. Those vehicles that are platooned are assumed to travel with a consistent intra-platooned headway while the remaining vehicles are assumed to have exponentially distributed time headways. Using this distribution, the author derived a minimum delay model for drivers entering roundabouts. Troutbeck (Austroads, 1993) went on to model average queueing delay for drivers entering a roundabout by

$$w_m = w_h + 900T \left[Z + \sqrt{Z^2 + \frac{mx}{CT}} \right] \qquad (1)$$

where w_m is the average queueing delay per vehicle (sec), w_h is the minimum delay (sec) when entering traffic is very low, T is the duration of the flow period (hr) (i.e. the time interval during which an average arrival demand, Q_m, persists (1 hr or 0.5 hr), x is the degree of saturation of the entry lane, C is the entry lane capacity (veh/hr), $Z = x - 1$ and m is a delay parameter given by $m = w_h C/450$. The second term in Equation (1) accounts for the presence of a queue on the entry lane to a roundabout. This is a time-dependent formula (Akçelik, 1991; Akçelik and Troutbeck, 1991) derived from the steady-state formula developed by Troutbeck (1989) and is recommended to be applied at roundabouts operating near capacity or in oversaturated conditions (Austroads, 1993).

Siegloch (1974) developed a delay prediction model based on gap acceptance theory for TWSC intersections. This empirical model uses the volume-to-capacity ratio (sometimes referred to as the *degree of saturation*) and is given by

$$d = \frac{3600}{v_s} \left[\exp\left(-v_s t_f\right) \cdot (1-x)^{-1} - 1 \right] \tag{2}$$

where d is the average delay to vehicles on the approach (in sec), v_s is the volume on the subject approach (vehicles/hour), x is the degree of saturation and t_f is the follow-up time or headway maintained between two consecutive entering vehicles utilizing the same gap.

Queueing theory has also been used to estimate delay at unsignalized intersections. Troutbeck (1986) applied the Pollaczek-Khintchine formula from queueing theory to estimate delay at minor approaches. The author's delay for an individual driver is given by

$$d = c_n^{-1} \left[1 + xC \cdot (1-x)^{-1} \right] \tag{3}$$

where x is defined as in Equation (1) and the constant parameter C is 1.0 for exponentially distributed service time and 0.5 for deterministicly distributed service time.

2.1 STATE-OF-THE-ART REVIEW FINDINGS

After reviewing several studies that addressed modeling the delay experienced by drivers entering unsignalized intersections, the authors agreed that little work had been completed in the area of modeling the time that a driver spends in the first position of the queue, hereafter referred to as service time. This fact despite that many of these models are based upon queuing theory. Traditionally, the inverse of approach capacity has been used as an estimate of service time. Authors have also used parameters to define if the service time was deterministicly or randomly related to the degree of saturation of the approach. In addition, most models assume the

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headways in the circulating stream are exponentially distributed and therefore it is not necessary to model the variance of service time. We set out to develop equations that could model the mean and variance of the service time. Knowing these two pieces of information, analysts could then apply the Pollaczek-Khintchine formula from queuing theory to estimate time spent in the system (time spent in the first position waiting to be serviced plus time spent in the queue). We also wanted to develop a model that was not dependent upon a specific distribution of headways in the circulating stream. In order to accomplish this, we used a generalized service distribution and modeled the queuing system of a single lane roundabout as an M/G/1 queuing regime.

3.0 METHODOLOGY

A methodology is presented by which the delay experienced by a vehicle on an approach to a single lane roundabout can be estimated. Figure 1 is included to assist the reader in understanding the steps required to estimate delay at a single lane roundabout according to this model.
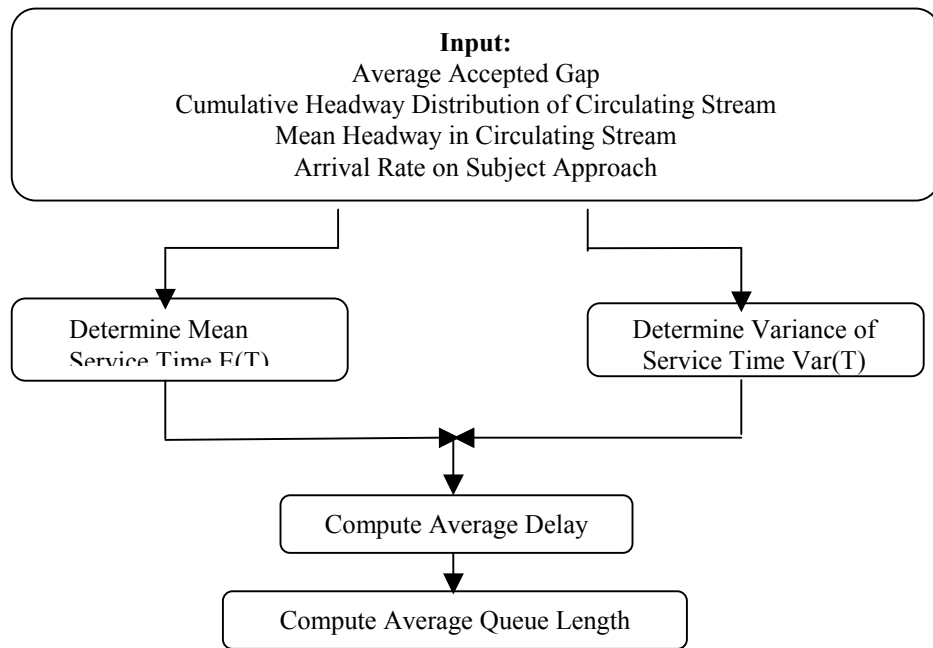
Fig. 1. Delay Estimation Methodology

On the approach of a single-lane roundabout, vehicles arrive at the yield bar and wait for an acceptable gap between subsequent vehicles in the conflicting traffic stream before entering

the roadway. If an arriving vehicle finds a vehicle already in the first position of the approach, then that individual must wait for entry of the first vehicle into the circulating stream before assuming the first position. On the other hand, if a vehicle arrives at the approach and finds no vehicles ahead of it, the driver immediately assumes the first position of the approach and awaits an acceptable gap to enter the circulating traffic stream. In reality, vehicles may not always come to a complete stop in this scenario, but rather, may simply decelerate before proceeding into the circulating stream. Figure 2 graphically depicts a typical roundabout in which the approach and circulating traffic stream are displayed.

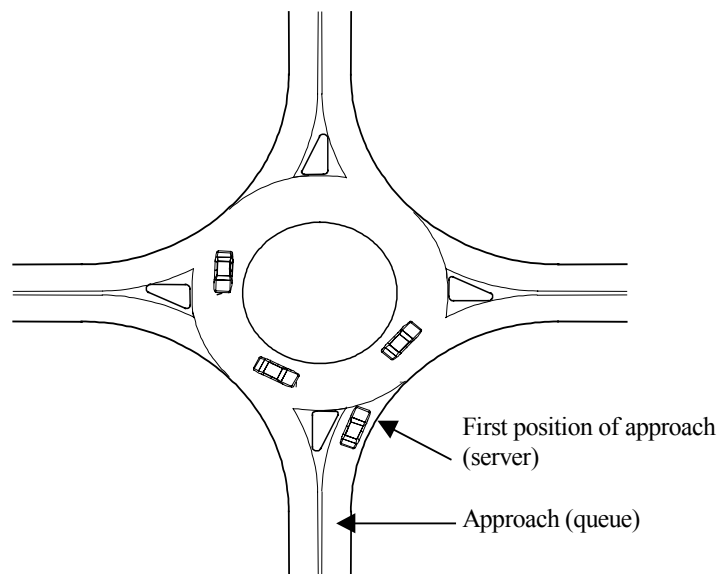First position of approach (server)

Approach (queue)

Fig. 2 Pictorial representation of a single-lane roundabout

This scenario of vehicles arriving to the approach and awaiting entry to the roundabout may be modeled as a queuing system. More specifically, the first position of the approach may be considered as the server in the queuing system and the queue is the waiting line of vehicles seeking "service" in the first position. If it is assumed that vehicles arrive to the approach according to a Poisson process, and that there is an infinite amount of physical capacity for vehicles waiting in line at the approach, then the approach may be modeled as an M/G/1 queue. Under this queuing regime, no assumptions are made concerning the service time distribution, or is it assumed that the service time is constant.

The true service time for a vehicle in the first position of the approach includes the time required to wait for an acceptable gap, travel time to enter the circulating stream and the headway for the subsequent circulating vehicle. It should be noted that the queuing model assumes instantaneous service (i.e. zero time for vehicle passage into the circulating stream). However, in field measurements, a vehicle is not considered serviced until the rear bumper of the vehicle clears the yield bar, which is typical in operations modeling. Adjustments to our model for this discrepancy are described in Section 5.2. The waiting time is the random time spent on the approach waiting to assume the first position in the queue plus the service time. Applying standard queuing results for the M/G/1 queue (see Gross and Harris 1985), the mean number of vehicles in the system (server and queue) is given by the Pollaczek-Khintchine formula

$$L = \rho + \frac{\rho^2 + \lambda^2\sigma^2}{2(1-\rho)} \qquad (4)$$

from which the mean waiting time can be obtained by Little's law as

$$W = \frac{L}{\lambda} \qquad (5)$$

where λ is the mean arrival rate to the queue, μ^{-1} is the mean service time of the server, σ^2 is the variance of the service time, and $\rho = \lambda/\mu$ is the traffic intensity. Clearly, Equations (4) and (5) require only the mean arrival rate of vehicles to the queue (λ) and the mean and variance of the service times having a general distribution, $G(\cdot)$. For our model, an infinite queue storage is assumed for simplicity. The mean and variance of the service time are obtained via renewal theory. A brief discussion of renewal theory adopted from Ross (1983) is discussed next.

Let $\{N(t) : t \geq 0\}$ be a counting process such that $N(t)$ denotes the number of occurrences of an event in the time interval $(0,t]$. Define X_n as the time between the $(n$-1$)^{st}$ and the nth event. The counting process $\{N(t) : t \geq 0\}$ is said to be a renewal process if the sequence of nonnegative random variables $\{X_1, X_2,...\}$ is independent and identically distributed with

arbitrary distribution function $F(\cdot)$. For example, when the distribution function of the interevent times is exponential, the counting process is said to be a Poisson Process.

A delayed process is one in which the distribution function for the first interevent time X_1 is $F_e(\cdot)$ while the sequence $\{X_n : n = 2,3,...\}$ follows the distribution $F(\cdot)$. The distribution function $F_e(\cdot)$, referred to as the equilibrium distribution, is related to $F(\cdot)$ by

$$F_e(t) = \tau^{-1} \int_0^t (1 - F(u)) du \qquad (6)$$

where $\tau = E(X_n)$. After the occurrence of the first event, the renewal process is initiated, and henceforth, all interevent times have cumulative distribution function $F(\cdot)$.

In the case of the single-lane roundabout, the sequence of observations, $\{X_1, X_2,...\}$, correspond to time headways for the circulating traffic stream. In the next sub-section, we present the main results of our paper; analytical models to compute the mean and variance of service time under a general headway distribution $F(\cdot)$.

4.0 MODEL DEVELOPMENT

Let T be a continuous random variable denoting the time for a driver to enter the circulating stream of a single-lane roundabout given that the driver is at the front of the waiting line (i.e. T is the service time). Our objective is to calculate the expected value and variance of T given that headway times for the circulating stream follow some general cumulative distribution function denoted by $F(\cdot)$. The first vehicle attempting to enter the circulating stream arrives at the approach at some intermediate phase of the renewal process and not at the beginning (i.e. with probability 1, the first driver does not enter the approach at the inception of a renewal epoch). Hence, the elapsed time until first passage of a circulating stream vehicle will not technically follow the distribution $F(\cdot)$, but can be assumed to follow the equilibrium distribution (see Equation (6)) of $F(\cdot)$. Figure 3 illustrates these concepts.
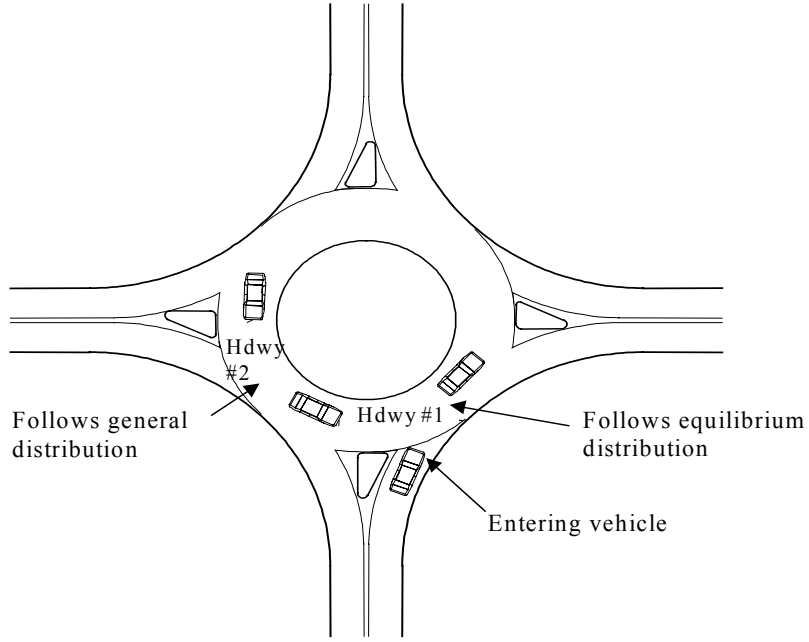
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Fig. 3. Graphical depiction of relationship between equilibrium and general distribution

Define g as the mean acceptable gap size for drivers arriving at the subject approach and τ as the mean time headway for circulating vehicles under the general distribution $F(\cdot)$. It is assumed in this preliminary work that all drivers in a particular study period use the same gap size. The expected service time may be obtained by conditioning upon the passage time of the first and subsequent vehicles in the circulating stream as

$$E(T) = \frac{1}{\tau}\left\{\frac{1}{2}g^2 - \int_0^g tF(t)dt + (1 - F(g))^{-1}\left[g - \int_0^g F(t)dt \int_0^g tdF(t)\right]\right\} \qquad (7)$$

Derivation of Equation (7) is provided in Flannery (1998).

Using a similar approach, the variance of service time may also be derived. From basic probability, the variance of a random variable, T, may be given by

$$VAR(T) = E(T^2) - \left[E(T)\right]^2$$

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Using this relationship, the variance of service time may be written by

$$VAR(T) = \frac{1}{\tau}\left(\frac{1}{3}g^3 + E(T_0)g^2 - \int_0^g \left(t^2 + 2tE(T_0)\right) \cdot F(t)dt\right)$$

$$+ \frac{1}{\tau}\left(g - \int_o^g F(t)dt\left(1 - F(g)\right)^{-1}\right) \cdot \left(\int_0^g t^2 dF(t) + 2E(T_0)\int_0^g tdF(t)\right)$$

$$- \left[E(T)\right]^2 \tag{8}$$

where the last term of (8) is obtained by (7) and $E(T_0) = \left(1 - F(g)\right)^{-1}\int_0^g tdF(t)$. See Flannery (1998) for a complete derivation of Equation 8. Note that Equations (7) and (8) require only the mean time headway of the circulating stream, the mean acceptable gap and the cumulative distribution function of the interarrival times of the circulating stream. In this study, the lognormal distribution was found to be the most appropriate distribution for the circulating stream headway distribution; however, many researchers have used the exponential distribution, as does the HCM 2000. If the headway distribution is assumed to be exponential with rate θ, then $E(T)$ and $VAR(T)$ are given by

$$E(T) = \theta^{-1}\left(\exp(\theta g) - 1\right) - g \tag{9}$$

and

$$VAR(T) = \theta^{-2}\left(\left(\exp(\theta g) - \theta g\right)^2 - 1\right) - g^2 \tag{10}$$

An analysis of the headway distribution from this field study is given in Flannery, et.al.(2000).

Equations (7) and (8) are utilized in the M/G/1 queueing model to obtain quality of service measures, namely the average number of vehicles on the approach given by

$$L = \lambda E(T) + \frac{\lambda^2 \left[(E(T))^2 + VAR(T) \right]}{2(1 - \lambda E(T))} \tag{11}$$

and the average waiting time on the approach (queue time plus service time), which is obtained by Equation (5).

The analytical models of this section require a value for the average accepted gap for individuals, the headway distribution of the circulating stream and the arrival rate to the roundabout approach. For this study, the authors made a decision to use the mean average accepted gap during each study period to estimate service time and the variance of service time. When estimating average delay for a particular study period, average accepted delay appeared more representative of field conditions than mean critical gap as has been traditionally used in past studies. On average, the mean accepted gap for the 43 study periods was 2.86 seconds longer than the calculated mean critical gap for the same time periods.

Estimation of the headway distribution may be achieved by collecting headway data under varying levels of traffic flow. Headway maintained by a pair of circulating stream vehicles is formally defined as the elapsed time between the front bumper of the first vehicle and the front bumper of the second circulating vehicle, based on some fixed point of reference. By collecting a sufficiently large number of headway observations at a roundabout site, an empirical distribution function may be obtained. Thereafter, it is possible to fit a parametric probability distribution to the headway data to be used in Equations (7) and (8).

5.0 FIELD OBSERVATIONS

5.1 Data collection procedure

Driver performance and operational data were collected at six single lane roundabouts located in Florida and Maryland for this study. The data collection sites are shown in Table 1 along with information regarding average daily traffic and peak hour volumes. Each site adheres to the basic definition of a roundabout in that it requires entering drivers to yield to circulating

traffic and their entries are deflected to slow drivers as they proceed through the roundabout. In addition, each site had been in operation for at least one year prior to data collection. Data were recorded at the six single-lane roundabouts by video cameras mounted at each of the roundabout entries and over the circulating roadway for two hours during the morning and evening peak periods.

Table 1. Summary of empirical study data collection sites

Location	No. of Approaches	Average Daily Volume on All Approaches (veh/day)	Peak Hour Volume on All Approaches (veh/hr)
Palm Beach County, FL	4	7600	510
Lisbon, MD	4	8500	856
Tallahassee, FL.	3	17825	1085
Fort Walton Beach, FL	3	12000	1245
Lothian, MD	4	15000	1345
Boca Raton, FL	4	16000	1450

Extraction of the data was performed on a video editing deck with shuttle jog control that allows the user to stop the video on a frame-by-frame basis ($1/30^{th}$ of a second). In addition to observing traffic volumes, the following operational performance measures were also observed:

- 15-minute entering flow rate per approach (veh/hr)
- 15-minute circulating flow rate per approach (veh/hr)
- turning movements (veh/hr)
- headway in the circulating stream (sec)
- gaps/lags in the circulating stream accepted by entering drivers (sec)
- gaps/lags in the circulating stream rejected by entering drivers (sec)
- follow-up time maintained by two consecutively entering vehicles (sec)
- service time (sec)
- time spent in the queue (sec)

These data were used to generate the parameters necessary to apply Equations (7) and (8) to estimate the mean and variance of service times under a particular set of conditions. More

information regarding the determination of headway distribution can be found in Flannery, et. al. (2000).

5.2 Summary of analytical results

To test the validity of modeling the service time and variance of service time to estimate system delay (service time plus time spent in the queue), a comparison was made between the Troutbeck model given in Equation (3), and the results of applying Equations (7) and (8) to estimate system delay. The Troutbeck model uses an indirect method of estimating service time by assuming that the inverse of the approach capacity is equal to the service time. In addition, the variance of the service time is indirectly accounted for by assuming deterministicly or exponentially distributed service times. Using the capacity equation for single lane roundabout approaches given in the HCM 2000, along with estimates of mean critical gap and mean follow-up time based on field data collected, the Troutbeck model was used to estimate system delay for 43 15-minute study periods. In addition, both the deterministic and exponential distributions of variance of service time were tested along with the performance of the newly developed model from this study. Finally, the performance of the Troutbeck delay estimation model and the model developed in this study were compared to field measurements of system delay collected at the six study sites.

Figure 4 contains a comparison of the Troutbeck model and the model developed as part of this study and presented in Equations (7) and (8). From this plot, the insensitive nature of the Troutbeck model as conflicting flows increase is shown. In comparison, as conflicting flows increase, the predicted system delay is shown to increase when the new model is applied, as would be expected. The merits of modeling the time spent in the first position of the queue, as this study does, are demonstrated in this plot. Next, the models' performance were compared to field measured system delay. Figure 5 contains a plot of the difference between field and model estimated system delay as conflicting hourly flow rates increases. From this plot, it is shown that under very low conflicting hourly flow rates, both models experience a few random periods when field delay is much higher than is predicted. These points can be considered outliers. However,

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as the conflicting hourly flow rates increase, the newly developed model appears to predict system delay more accurately than the Troutbeck model.

Figure 4
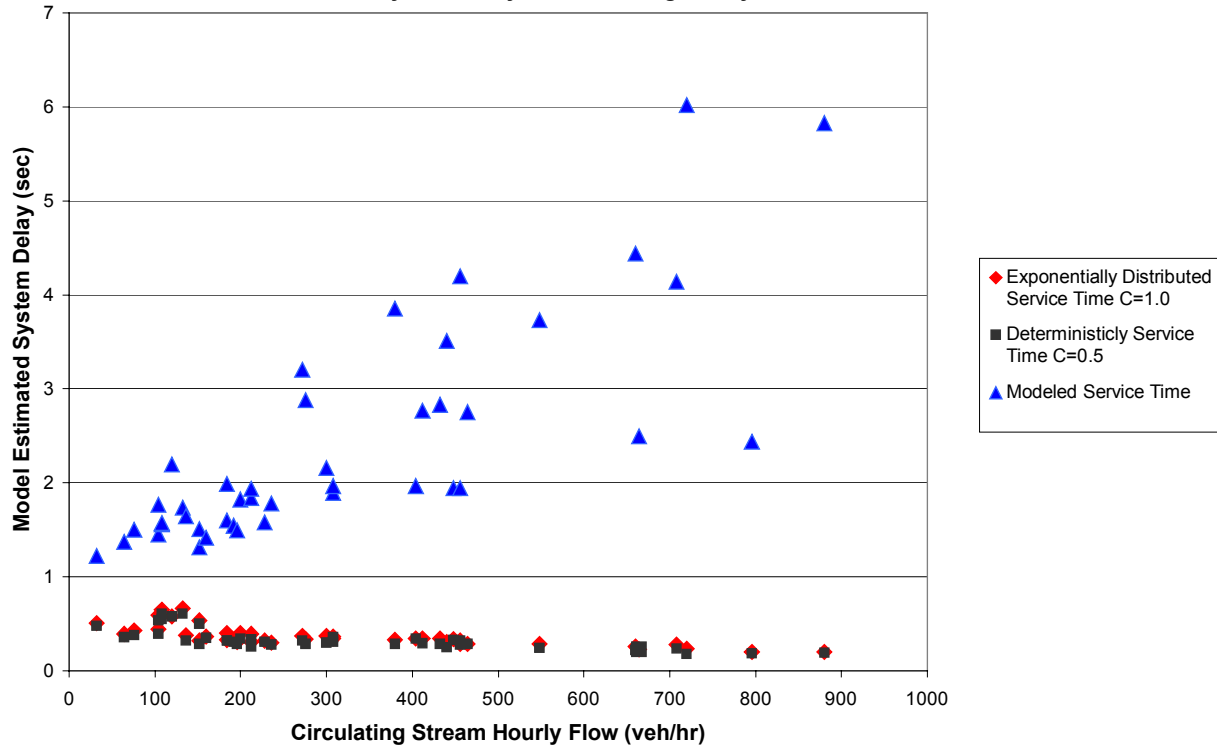**Model Estimated System Delay vs. Conflicting Hourly Flow**

Figure 5
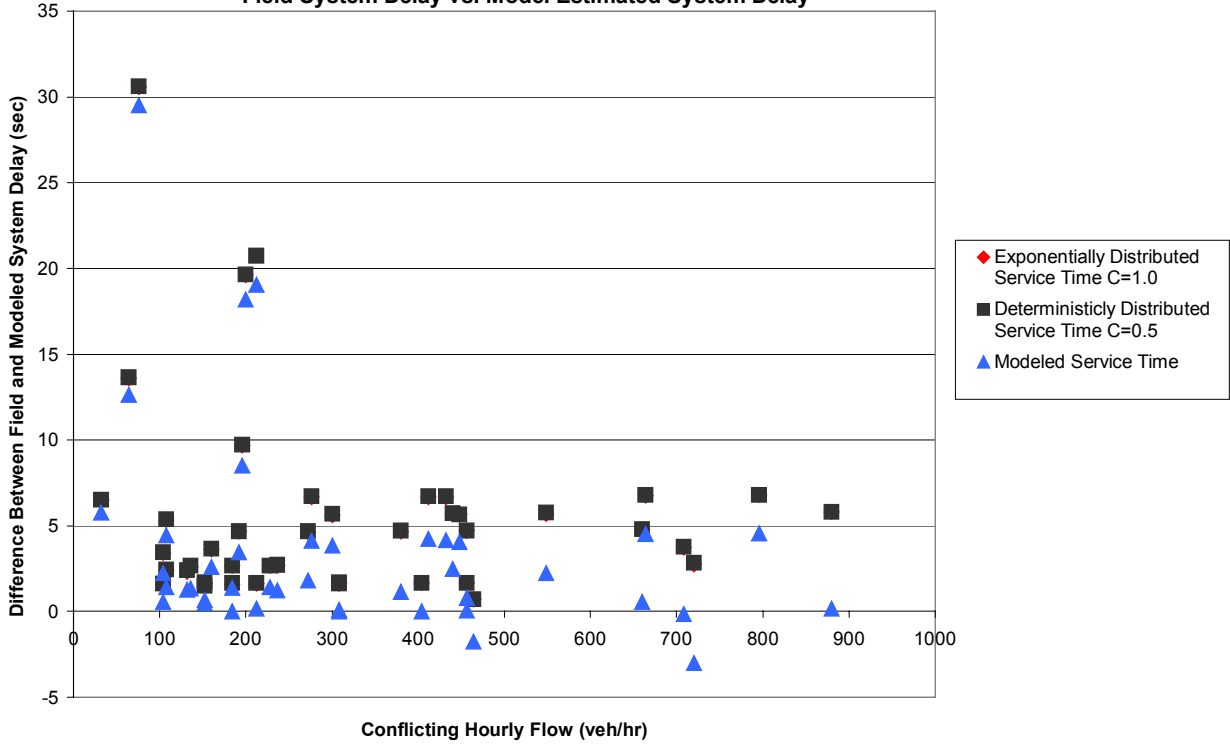**Field System Delay vs. Model Estimated System Delay**

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Table 2 gives a summary of the performance of the newly developed models as compared to the field data, using a lognormal distribution to represent headways in the circulating stream, as was found to most represent field observations. The results indicate that in 43 cases, the mean absolute deviation between the model's predicted value and the field data is 1.27 sec and the maximum absolute deviation was 6.95 sec. A similar comparison is made for the standard deviation of service time.

Table 2. Deviation between field and model values (lognormal headway)

Statistic	Mean Service Time (sec)	Std. Dev. Of Service Time (sec)
Mean Absolute Deviation	1.2710	1.3727
Maximum Absolute Deviation	6.9500	6.0784

The discrepancy between the new model and field results may be attributed to a few different factors. First, our model assumes that the roundabout approach behaves exactly as a queueing system in which vehicles move out of queue and into service in a stop-go fashion. In reality, if drivers observe an acceptable gap while approaching the first position, they tend to simply decelerate and then proceed directly into the circulating stream without stopping. This behavior is not captured in our model. Second, the queueing model assumes instantaneous service or zero time for vehicle passage into the circulating stream. However, when service times were measured in the field, a vehicle was not considered serviced until the rear bumper of the vehicle had cleared the yield bar, which is typical in operations modeling. In order to adjust for this discrepancy between the model and field measurements, the average vehicle passage time was added to the model estimate of mean service time (Equation (7)). This time, which was observed from several time periods and sites, was found to be about 1.0 sec on average. Third, the headway distribution of the circulating stream has been approximated by the lognormal distribution, although the true headway distribution is unknown.

5.3 Example Application of Models

The following example problem illustrates the procedure presented in Section 5 for determining delay for a single for a single lane roundabout. The data in this example problem were collected at the Fort Walton Beach, Florida roundabout.

During the AM peak period the following data were collected:

Entering Hourly Flow	180 vph or 0.05 veh/sec
Circulating Hourly Flow	720 vph
Entering Lane Width	13 ft
Circulating Lane Width	20 ft
Average Headway in the Circulating Stream	6 sec^{-1}
Variance of Headway in the Circulating Stream	43 sec^{-2}
Average Accepted Gap	4.4 sec
Follow-up Time	2.2 sec

Estimated delay is determined by first applying Equations 7 and 8 to determine the expected service time and the variance of that service time, respectively. For this time period the *E(T)* and *Var(T)* is determined:

E(T)	2.50 sec
Var(T)	13.68 sec

Recall the model results do not account for the time it takes the vehicle to cross the yield bar, therefore, an additional second is added to *E(T)* to be compared to field measurements. Likewise, one second is added to *Var(T)* yielding a modified *E(T)* and *Var(T)* as follows:

E(T) modified	3.5 sec
Var(T) modified	14.68 sec

Next, applying the Pollaczek-Khinchne model, the average number of vehicles in the system is determined:

$$\Delta = 8\vartheta$$

$$= (0.05 \text{ veh/sec})(3.5 \text{ sec/veh})$$

$$= 0.14 \text{ (unitless)}$$

Now L is determined by Equation 11:

$$L = 0.175 + \frac{1}{2} \cdot \frac{(0.175)^2}{(1-0.175)}(1 + \frac{(14.68)}{(3.5)^2})$$

$$= 0.216 veh$$

Using Little's Law, the average waiting time in the system or stopped delay is determined:

$$W = \frac{L}{\lambda}$$

$$= \frac{0.216 veh}{0.05 veh / \sec}$$

$$= 4.3 \sec$$

6.0 CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

This paper provides analytical models to estimate the mean and variance of service time for a driver in the first position of a single-lane roundabout approach. The mean and variance of service time are used in the Pollaczek-Khintchine formula to derive expressions for the average number of vehicles awaiting entry to the circulating stream and the average total waiting time for an individual (i.e. service time plus time in queue) entering a roundabout. The model exhibits flexibility in that it facilitates the use of any headway distribution for the circulating traffic stream. The performance of this model was compared to a similar queuing model developed by Troutbeck which does not attempt to model service time or the variance of service time. The results are encouraging in that the new model appears to more accurately model system delay

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than previous models. Such an analysis contributes to a better understanding of operational characteristics of single-lane roundabouts in the United States.

Several important findings emerge from our analytical and empirical studies. First, data collected from six single-lane roundabout sites indicate that headway times of the circulating stream are most closely approximated by the lognormal distribution. These findings confirm similar study findings by Gerlough and Huber (1975) and Bissell (1960). For this reason, the lognormal distribution is used in the analytical models. Also, when compared against the field data, we find that the preliminary analytical models predict the mean and variance of service time fairly well based on the average and maximum absolute deviation.

The use of roundabouts as an alternative to standard intersections is increasing rapidly in the United States. As the number of roundabouts increases, more data will become available to help refine and improve the models proposed herein. Hence, a number of future research directions may be identified. First, this work assumed that all drivers use the same gap acceptance criteria for entering the circulating stream (the mean acceptable gap). It would be useful to investigate the effects of geometrical or operational characteristics that are influencing gap acceptance behavior of entering drivers and consider this gap as a random variable. Another extension would be to model the components of service time that were assumed fixed in our preliminary model (i.e. car lengths, travel time into the stream, acceleration/deceleration) as a random component. Finally, this work serves as a stepping stone for the analysis of multi-lane roundabouts. The complexity of the multi-lane problem is significantly greater due to complex weaving patterns in the circulating roadway and gap acceptance behavior of entering drivers. Thus, an analysis of the headway distribution of the circulating traffic stream and the gap acceptance behavior of simultaneously entering vehicles is needed. This can possibly be used in a multiple server queueing model.

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