The Potential for Metering to Help Roundabouts Manage Peak Period Demands in the US

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ABSTRACT

Roundabouts generally provide safety and other advantages. During peak hours, however, even moderate demands on an upstream approach can result in long delays for downstream movements. Metering is one way to ensure that all demands at a roundabout are adequately served. A roundabout meter is a signal that regulates flow into the circle from one approach, thereby creating larger gaps in the circle for downstream entrants. Although roundabout meters have been used successfully around the world, there is little guidance available for US designers. The goal of this research was to provide US designers with some guidance on the use of roundabout meters. The authors developed a simple macroscopic model based on the Highway Capacity Manual, validated it using a simulation model, and exercised it on a number of demand combinations to see where a meter might help.

The macroscopic model should be helpful as a quick screening tool. The results from application of the model provide evidence that a meter will reduce delay compared to an unmetered roundabout with some demands. While signals produced lower delays than metered or unmetered roundabouts in most cases tested, sometimes roundabouts were better. Analysts should consider more than just peak period delay in deciding on the optimum traffic control at an intersection. If a roundabout, with the aid of a meter for a few peak hours, produces slightly higher delay levels during those peak hours than a signal, considering its many other benefits it could well be the optimum design.
INTRODUCTION

Roundabouts with one- or two-lane circulating roadways are generally safer than comparable signalized intersections, are attractive, have a reasonable life-cycle cost, and are more efficient for travelers throughout non-peak hours which constitute the vast majority of the day’s hours and traffic. During peak hours, however, even moderate demands on an upstream approach coupled with standard yield-on-entry roundabout priority rules can result in long delays and frustration for certain downstream movements. Finding a way to ensure that demands from all approaches can be adequately or better served under unbalanced flow conditions could increase the viability of roundabouts as an intersection option by mitigating its operational performance inadequacies during those conditions and enable the traveling public to gain the advantage of the superior off-peak operational and all-day safety benefits of roundabouts at more locations.

Metering is one way by which agencies could ensure that all demands at a roundabout are adequately served. A roundabout meter is a signal on an approach that regulates flow into the circle from that approach, thereby creating larger gaps in the circle that downstream entrants can use. A meter is typically placed some distance upstream from the yield line—in this research we used 65 feet or 20 meters—to allow pedestrians to benefit from the signal and to provide space for at least a couple of vehicles to queue at the yield line without blocking the exit from the signal. Meter signals do not apply to traffic in the circle, which still enjoys the right-of-way. Meter signals can have two aspects (red and yellow) or three aspects (red, yellow, and green), with the through indication being conveyed by a blank indication, a flashing yellow, or a green. A roundabout meter would likely be needed on only one or two of the approaches to a four-legged roundabout: the minor approach just upstream (to the left) of the approach with the heavy demand in the morning peak period, and/or the minor approach just upstream (to the left) of the approach with the heavy demand in the evening peak period. Since a meter is a way to add capacity to an approach during peak periods, it should rarely be needed for more than an hour or two per day. In fact, a roundabout meter may be actuated, tied to a queue detector established on the major approach some distance upstream of the yield line so it is only activated at needed times during the peak period.

The literature on roundabout metering shows that they have been used successfully elsewhere in the world, and particularly in Australia. However, roundabout meters are rare in the US; the authors know of only two such installations. In addition, while research on roundabout meters has been performed in Australia and elsewhere, the authors know of no research in the US that provides guidance to analysts interested in this treatment. There is no equation, procedure, or software for US designers to use. US analysts can always employ VISSIM or other microscopic model to analyze a roundabout meter, but that is expensive and time-consuming. This is an important and troubling knowledge gap for US designers and analysts, denying them a chance to use a promising device.

Objectives

The overall goal of this research, then, was to provide US designers with some guidance on the use of roundabout meters. In particular, the authors aimed to:
Develop a simple macroscopic model based on the 2010 *Highway Capacity Manual* (HCM, 1) that analysts could use to quickly screen candidates for roundabout meter installation;

- Validate the macroscopic model using a microscopic simulation model; and
- Exercise the macroscopic model on a number of realistic demand combinations to see where a meter might make sense in comparison to an unmetered roundabout or a conventional signalized intersection.

Achievement of these three objectives will hopefully provide some guidance to US designers so they can start considering roundabout meters at appropriate locations. If roundabout meters prove to be helpful in some spots, that could increase the range of applicability for roundabouts and allow the benefits mentioned above—particularly the safety benefits—to spread. Roundabout meters could lead to substantial collision savings if widely applied.

**Scope**

The scope of this research was limited in several important ways. The results only apply to:

- Roundabouts with four approaches, standard geometry, and no bypass lanes;
- Roundabouts with one meter installed;
- Driver behavior as captured in the equations of the 2010 HCM (1), with one exception as noted below;
- Roundabouts with no trucks, pedestrians, or other factors that affect capacities; and
- Simple meter designs with fixed cycles and no actuation.

Other limitations will be mentioned in the sections to follow. Some of these limitations will require more research to overcome, while others will just require analysts to make simple adjustments for particular field situations.

**PREVIOUS LITERATURE AND PRACTICE**

Most of the application of roundabout metering in the world to this point has been in Australia, particularly in the State of Victoria. These have been documented extensively by researchers including Akcelik (2-6). Akcelik (6) notes that, "Roundabout metering signals help to create gaps in the circulating stream to solve the problem of excessive queuing and delays caused by unbalanced flow patterns and high demand flow levels." Akcelik (3,6) used the SIDRA intersection analysis model to identify queue length, signal timing, and other operational parameters. An examination of a roundabout in Melbourne, Victoria, Australia demonstrated that various timing strategies were possible to optimize peak hour operations. Natalizio (7) used an early version of the Akcelik model to find volume combinations for single-lane roundabouts in Australia where metering would provide benefits. Others, such as Andjik (8), have used microscopic simulation models to analyze the potential of meter installation at case study locations.
VicRoads, serving the Australian State of Victoria, describes metering signals in its traffic management note on intersection control, stating that they have “a proven effectiveness at a number of sites in Victoria.”(9). Keeping in mind that driving in Australia is to the left, that note states that roundabout performance “is sensitive to unbalanced traffic flows. This may occur where the entering traffic from a dominant leg prevents traffic from the adjacent or affected approach to the left of the dominant flow from entering the roundabout. This situation results in excessive queues and delays in the affected approach.”

The VicRoads note mentions that the dominant traffic flow that causes operational challenges for a downstream approach could be either: "a high uninterrupted traffic flow" or "a low but consistent flow from a minor approach that takes priority over a major flow". For either case, the report states that the resulting operational deficiency "can usually be addressed by the provision of part time metering signals that regulate the dominant flow and provide gaps in the circulating traffic. This enables the traffic from the affected approach to enter the roundabout."

The VicRoads note states that metering signals can afford several benefits at the intersection, including:

- Management of the peak flows to provide appropriate priority for a major movement,
- Provide better balance of queues and delays between approaches, and
- Extend the life of a roundabout rather than require its replacement.

In terms of installation strategy, the VicRoads note states that while metering signals are "generally considered as a 'short term fix' stage when problems develop due to changing traffic flows over time", they also could at certain locations "be considered as part of a new roundabout control to proactively manage the traffic. This form of control may avoid the need for installation of intersection traffic signals and retain safety and operational benefits at times of lower flow at the roundabout."

Metering is also used in New Zealand. The New Zealand Transport Agency (10) described metering as a:

method for controlling a roadway entering a roundabout. The intent is to manage the entering flow of traffic on that roadway because it periodically: receives a disproportionate level of priority, causing major delays on one or more other entering roads, causes queues on another leg across a nearby level (at-grade) crossing which must be cleared for an approaching rail vehicle, may hinder the passage of emergency vehicles through the roundabout, (and) may impose delays on public transport movements through the roundabout seriously impacting on service reliability.

Roundabout metering has been discussed in the United States and applied at least a couple of times. NCHRP 672 (11) includes a mention of roundabout metering: "During peak periods, it is possible for the flow from one entry to dominate downstream entries to the point where insufficient gaps are available, causing excessive delays and queues at the downstream entry. In these cases, entrance metering can provide significant operational benefits during these peak periods. In some cases, metering may be a more economical solution than geometric
Improvements, especially if the traffic condition requiring metering is of a short duration.” The NCHRP report provides a diagram and photo of the approach signal at Clearwater Beach, FL, as well as two in Australia. The Clearwater Beach roundabout, described by Sides (12) has been a tremendous success from a safety as well as operational standpoint, due to the replacement of numerous intersections by a safer roundabout as well as the provision of the metering signal.

Members of this research team also visited the metered roundabout at the Snowden River Parkway interchange with the Maryland Route 100 freeway near Columbia, MD. That location has an on-demand preemption signal that has, based on anecdotal reports, reduced delay on the freeway exit approach to the three-leg roundabout.

MODEL DEVELOPMENT

Our search of the literature revealed no procedure to analyze metered roundabouts based on US driving habits. US analysts can use Akcelik’s procedure from Australia or a microscopic simulation model to analyze a particular roundabout with and without a meter, but US drivers behave quite differently from Australians at roundabouts and a microscopic simulation analysis is difficult and costly to calibrate. To fill the need for a US-based analytical procedure for metered roundabouts, we developed our own based on HCM (1) equations.

The analytical procedure we developed for this effort applies to a meter on one approach of a roundabout with four approaches. As Figure 1 shows, the approach downstream from the metered approach is called the “controlling” approach as it is the one that we wish to experience a shorter queue at some times. The other two approaches are called the “right of controlling” and the “opposite from controlling”. The objective of the procedure was an estimate of the change in delay, in seconds per vehicle, due to the meter, on the metered and controlling approaches. The other two approaches may also experience some change in delay due to the meter, but the magnitude of those changes is likely very small relative to the metered and controlling approaches. The description that follows is for a one-lane roundabout with one lane approaches, although the extension to two-lane roundabouts is easy.

Figure 1. One-lane roundabout with meter.
The equation for predicting control delay in an approach lane of a roundabout in the 2010 HCM (1) is:

\[ d = \frac{3,600}{c} + 900T \left[ x - 1 + \sqrt{(x-1)^2 + \left( \frac{3,600}{c} \right) x + \frac{450T}{T}} \right] + 5 \times \min[x,1] \]

Where \( d \) is delay in seconds per vehicle, \( c \) is capacity in vehicles per hour, \( T \) is the time period of interest for the analysis in hours, and \( x \) is the flow rate to capacity ratio. Since \( T \) is typically 0.25 and flow rate is a straightforward function of demand, the main term in the equation is the capacity.

In the 2010 HCM (1) the equation for the capacity of a one-lane approach to a one-lane roundabout is:

\[ c_{pce} = 1,130e^{-1.0 \times 10^{-5} t_c,v_{c}} \]

Where the subscript pce refers to passenger car equivalents and \( v_{c} \) is the flow rate of conflicting traffic in the circle in front of the approach of interest. For the remainder of this discussion we assume that there are no heavy vehicles, pedestrians, or other factors causing the need for adjustments, so that the \( c \) calculated in this equation can be inserted directly in the delay equation, although it is not difficult to make adjustments for heavy vehicles or pedestrians if needed. The constants in the capacity equation above, 1130 and -0.001, are related to the critical follow-up time and headway for vehicles entering the circle, respectively, as shown in the following equations from the 2010 HCM (1):

\[ c_{pce} = A e^{(-B v_c)} \]

\[ A = \frac{3,600}{t_f} \]

\[ B = \frac{t_c - \left( \frac{t_f}{2} \right)}{3,600} \]

Where \( t_f \) is the follow-up headway and \( t_c \) is the critical headway. The constant 1130 in the capacity equation is, in effect, the “ideal” capacity of a one-lane approach to a roundabout that has no conflicting traffic and corresponds to a \( t_f \) of 3.18 seconds. This constant has been
criticized by many observers; for example, engineers from Carmel, Indiana, a city that has adopted roundabouts as its primary form of traffic control at important intersections, conveyed to the authors that the constant should be more like 1500 (corresponding to a t_r of 2.4 seconds) for roundabouts in their city due to driver learning at the many roundabouts.

In our analytical model, delay estimation on the metered approach is different from delay estimation on the controlling approach.

**Delay on the Metered Approach**

On the metered approach, traffic is delayed by the meter then by the conflicting traffic in the roundabout. Overall control delay for traffic on the metered approach is the sum of the delays at the meter and the circle. At the signal, we can assume two-phase operation with some lost time at the beginning and end of the green and yellow phase, then apply standard *Highway Capacity Manual* control delay equations. At the roundabout, we make the key assumption that control delay can be estimated by the *Highway Capacity Manual* method outlined above. The *Manual* states that the roundabout methodology, “does not account for the effects of adjacent traffic control devices such as nearby traffic signals…” This is due to the nonrandom arrivals at the circle and the effects of queues from the circle backing up to block the signal stop bar. In this model we assumed that overall control delay was simply a sum of the delay from the signal and the delay from the circle; we recognize that on the metered approach delay estimates at the roundabout are potentially underestimated, especially in cases with shorter green times that cause more platooned arrivals at the circle. We will explore this key assumption using VISSIM in the next section of the paper.

**Delay on the Controlling Approach**

On the controlling approach, delay will be different for traffic arriving when the meter is green and arriving when the meter is red. When the meter is green, controlling approach arrivals at the circle experience the same type of operation as in the unmetered case, and the capacity calculation is as described above. When the meter is red, the traffic arriving at the circle on the controlling approach will only experience conflicting traffic which originated on the approach opposite the controlling approach and is making a left turn (assuming no u-turns and neglecting travel time from the meter to the circle in front of the controlling approach). Thus, the capacity for that movement during that time will be considerably higher than when the meter is green. Overall capacity for the controlling approach should be an average of the capacities during the red and green weighted by the duration of each phase, or:

\[ c_{ca,m} = \frac{r \cdot c_m + g \cdot c_u}{r + g} \]

Where \( c_{ca,m} \) is the overall capacity of the controlling approach with meter operation in vehicles per hour; \( r \) is the meter effective red time in seconds; \( c_m \) is the capacity of the controlling approach with the only conflicting traffic being left turns from the opposing approach, in vehicles per hour; \( g \) is the meter effective green time in seconds; and \( c_u \) is the capacity of the controlling approach with the all conflicting traffic present, in vehicles per hour. The variables \( c_m \) and \( c_u \) are each calculated using the HCM capacity equation provided above. After the calculation of the overall capacity for the controlling approach, the delay equation is applied.
As mentioned earlier, follow-up times may be lower than the *Highway Capacity Manual* default values under some circumstances like driver learning. Another time that follow-up times may logically decrease is when driver perceive that conflicting traffic in the circle is negligible, due to a meter on the adjacent approach for example. Thus, the researchers experimented with the ideal capacity in the equation for \( c_m \) being as high as 1500 vehicles per hour, as shown in the following sections.

**VISSIM AND SYNCHRO SET-UP**

The researchers used VISSIM, a popular microscopic traffic model, to validate the macroscopic model described above and to find the signal timing at which the metered approach started to experience extra delay due to the interaction between the queue at the circle and the signal. The researchers constructed networks with standard geometry for one-lane and two-lane roundabouts. A simple two-phase pre-timed signal located 65 feet upstream of the entry yield line was used for the metered approach.

The simulation runs reported below were performed using calibrated roundabout VISSIM models. Each scenario was evaluated using 10 different random number seeds. The models were simulated for one hour (3600 seconds).

The calibration of the approach capacity was set to replicate the roundabout capacity relationship for roundabouts in the 2010 HCM (1), as generally described in Schroeder (13). Additional calibration for this research consisted of modifying speeds in reduced area at the entry of the roundabout from 9 mph to 7 mph and adjusting the value for a car-following parameter called the “multiplicative part of safety distance” from 3 to 7. With these adjustments, the team concluded that VISSIM was matching the macroscopic model results as well as possible for the case of an unmetered roundabout, and we were ready to compare results between the simulation and the macroscopic model with meters installed.

The researchers used Synchro, a popular macroscopic traffic model, to compute delays for cases of interest with conventional signals installed and compare those delay results to delay results estimated using the macroscopic model for roundabouts with and without meters. We used Synchro for cases with one through lane per approach and two through lanes per approach. On all approaches to a signalized intersection, we assumed that there was a one-lane, 400-foot long left turn bay; we did not use any exclusive right turn lanes on any approaches. As mentioned earlier, we analyzed these intersections with no saturation flow adjustments like grades, bus stops, trucks, pedestrians, or bicycles. Right turn on red was allowed. The delay results we report below are the “HCM-calculated delay” from Synchro.

Results for signals were based on optimized, fixed-time cycles. We used the Synchro default optimum cycle length or the minimum cycle length suggested by the North Carolina DOT based on the number of phases, whichever was higher. In all cases tested the cycle length ended up no lower than 60 seconds and no higher than 150 seconds. We used cross-products published in the 2000 *Highway Capacity Manual* (14) to determine if an approach needed a left turn phase; if the calculated cross-product exceeded the 2000 HCM limits we provided a protected-permitted
phase scheme. About half the one-lane cases tested, and almost all of the two-lane cases, needed protected-permissive phasing.

RESULTS

Validation

Figure 2 shows the key results from the VISSIM validation exercise. The figure shows, for one-lane and two-lane roundabouts with particular demands, how VISSIM estimates of delay compare to delay estimates from the macroscopic model we developed. The delay statistics in the figure are averages of the delays on the controlling approach and the metered approach. The comparisons are made across different levels of v/c at the meter, which is equivalent to green time (higher v/c at the meter means lower green times). The demand levels in Figure 2 were chosen to be representative cases that would be somewhat congested without the meter and where the meter could be helpful. The one-lane demand levels should cause more congestion than the two-lane demand levels.

Several observations can be made from Figure 2. First, at a v/c of 0.0, which means unmetered operation, the calibration exercises described above were successful and the average VISSIM delays were comparable to the average delays estimated by the analytical model.

Second, as the v/c went up, for both the one-lane and two-lane cases the VISSIM delays kept in step with the analytical delay estimates for the controlling approach. The VISSIM and analytical delays are consistently within 10 to 15 seconds per vehicle in both cases throughout the range of v/c. This is strong evidence for the validity of the analytical model.

Third, and equally important, Figure 2 is providing evidence of the signal timing at which the delay on the metered approach can no longer be estimated well by the analytical model due to the interaction between the circle and the signal. The point, where the delay estimates for simulation and analytical models significantly diverge for the metered approach, is around a v/c of 0.4 for the one-lane (more congested) case and above 0.8 for the two-lane (less congested) case. Future researchers interested in roundabout meters can help at this point by conducting a much larger set of simulations to find this point of interest for a wide range of demands, or by adapting the Akcelik model from Australia which considers interaction between the signal and the circle (6) to US conditions. In the meantime, the results for the analytical model shown in the rest of this paper are based on a conservative meter timing equivalent to a v/c of 0.45 so that we can be sure that in most cases reported the extra delay due to interaction between circle and signal is negligible.
A v/c ratio of 0.0 means that the approach is operating unmetered.

Figure 2. VISSIM results.
Effects of Metering
Having shown the validity of the macroscopic model against VISSIM results, and established a meter timing policy that should work for most demand levels of interest, the researchers exercised the model to see how well a meter would perform. Figures 3 and 4 show a summary of that exercise. The data in Figures 3 and 4 are for an interesting range of demands on the metered and controlling approaches; note that the demands on the other two approaches to the roundabout were assumed equal to the demand on the metered approach. The turning percentages assumed on all approaches were 20 percent left, 60 percent through, 20 percent right, and zero u-turns.

Delay statistics used for Figures 3 and 4 are average control delays for all four approaches to the roundabout. The top portion of Figures 3 and 4 assume that the ideal capacity at the yield line on the controlling approach remains the same at all times at 1130 pcp/hpl, while the bottom portions of Figures 3 and 4 assume that the ideal capacity at the yield line increases to 1500 pcp/hpl (i.e., the follow-up time decreases to 2.4 seconds per vehicle) when the meter is red and huge gaps are created in the circulating traffic stream. Readers should probably think of these two levels of ideal capacity as extremes in the US, with 1130 pcp/hpl more appropriate for novice and timid roundabout users and 1500 the top of the range as US drivers learn to use unmetered and metered roundabouts more aggressively.

The diamond symbols in Figures 3 and 4 represent demand combinations when the meter did not improve average delay by more than 10 seconds per vehicle. These are cases with lower demands, when the unmetered roundabout is generally working well and a meter is not needed. The square symbols in Figures 3 and 4 represent demand combinations when the meter improved average delay by more than ten seconds, but the average delay remained above 80 seconds per vehicle, which is the level of service F criterion for a signalized intersection. Here, meters are helpful but delays still may not be tolerable and other design or control measures may be needed at the intersection to create acceptable performance in the peak period. The triangle symbols in Figures 3 and 4 represent demand combinations when the meter improved average delay by more than ten seconds and the average delay remained below 80 seconds per vehicle. This is the “sweet spot” for roundabout meters where analysts should strongly consider them. The triangle symbols define “slices” through the middle of the figures, generally increasing in width to the left as the demands become less balanced. There are no triangle symbols on the top portion of Figure 3; in Figure 4 the slice is thicker when the ideal capacity for the controlling approach at the circle during red increases to 1500 pcp/hpl.
Capacity when meter is red = 1130 pcph

Capacity when meter is red = 1500 pcph

Figure 3. When metering is helpful for one-lane roundabouts tested.
Capacity when meter is red = 1130 pcp/hpl

Figure 4. When metering is helpful for two-lane roundabouts tested.
Figure 5, for the one-lane roundabout demand combinations tested in Figure 3, shows the results from the macroscopic model in a different way. From these data, we can discern an easy trigger point for when a meter would start to be helpful. It is apparent that somewhere between a v/c of 0.9 and 1.2 on the controlling approach a meter would begin to produce delay savings of 10 seconds or more over an unmetered roundabout.

![Figure 5](image.png)

*Figure 5. Demand to capacity as trigger for meter at one-lane roundabout.*

**Comparison to Signal**

Figures 3-5 showed, for the demand combinations tested, when a meter would improve operations at a roundabout. We wanted to go beyond that question, though, and provide guidance on the broader question of whether and when a roundabout meter would improve operations compared to a traffic signal. Thus, Figure 6 and 7 summarize delay estimates for metered and unmetered roundabouts from our macroscopic model to delay estimates for conventional signalized intersections from Synchro as described above. Delay in all cases is an average across all four approaches.
Figure 6. Delay at unmetered roundabouts, metered roundabouts, and signals for one-lane approaches.
Figures 6 and 7 show the same pattern. Signals generally produced lower delays for the two highest levels of controlling approach demand tested. For the third highest level of controlling demand tested, the metered roundabout became competitive with or surpassed the performance of the signal when the roundabout drivers behave aggressively with an ideal capacity at the circle for the controlling approach during red of 1500 pcppl. For the lowest level of controlling demand tested, neither the signal nor the metered roundabout substantially improves upon the delay performance of the unmetered roundabout across most cases, with the signal being the worst form of traffic control in some cases.

CONCLUSIONS AND RECOMMENDATIONS

The results above provide clear evidence that installing a meter on roundabouts with some demand combinations will reduce delay compared to an unmetered roundabout. In particular, there appears to be a ‘slice’ of demand combinations in which a meter on the relatively minor approach to the left of a more major approach will reduce average delay for all motorists. In this slice, the increase in delay for minor approach vehicles will be more than offset by the decrease in delay for the major approach. When demands on the approaches grow from those in the slice, the meter may still help reduce average delay but the delay levels on one or more approaches
become onerous and other treatments, such as widening or signalization, will likely be needed. The slice of demand combinations within which meters are effective changes between one-lane and two-lane roundabouts, but the pattern is similar. The slice of demand combinations within which meters are effective grows if drivers on the major approach shrink their follow-up times during times when the meter is red, but even assuming that the sluggish follow-up times in the 2010 HCM stay in place while the signal is red, metering the roundabout still could help in many circumstances. Overall, the results shown above make a strong case that those analyzing a roundabout that could get congested at some time during the day should at least consider a meter.

The results showed that signals would likely produce lower average control delay than roundabouts, metered or unmetered, in most cases tested. The difference in average control delay between signals and roundabouts was very large in some cases, but only modest in others. These differences should not be interpreted as evidence that signals are the optimum form of traffic control at those intersections, however. Analysts should consider much more than just peak period control delay in forming a conclusion on the optimum form of traffic control at an intersection. If a roundabout, with the aid of a meter for a few peak hours of the day, produces slightly higher delay levels during those peak hours than a signal, similar delay values for other hours, lower delay values for much of the day, superior safety performance, and many other benefits, it is likely the optimum at that site.

Analysts interested in examining a meter on a roundabout could use the model developed for this paper to take a quick look at the feasibility of the device. The model is easy to use, the logic is straightforward, and the results compared well to microscopic simulation for those cases tested. The model has an important limitation, in that it does not take into account delay incurred due to the close spacing of the signal and circle on the metered approach, so users should apply it only with generous green times (v/c < 0.5) to ensure that the interaction is not serious. Analysts can always use VISSIM or other microscopic model to analyze a proposed roundabout meter, but that process would be difficult and expensive, so the model developed herein should be handy as a screening tool.

**Future Research Needs**

Hopefully this paper will have interested US analysts in the idea of a metered roundabout to aid in handling peak period demands and will have provided an analytical tool for a quick look at that possibility. However, this paper is unlikely the last word in metered roundabouts, and there are several promising areas for researchers interested in advanced the state of the art, including:

- An improved analytical model for metered roundabouts in the US that takes into account the interaction between the signal and the circle on the metered approach. To this point, analysts must either apply Akcelik’s model (2011b) from Australia or use the model developed for this paper with green times that are high enough to ensure that no significant delay effects are registered.

- More guidance on optimum meter timing, once an improved analytical delay model is developed.
Once enough sites are available, field testing the improved delay model at metered roundabouts in the US.

Further into the future, examining the safety impacts of roundabout meters in the US.

At all types of roundabouts, metered or unmetered, monitoring follow-up times to see if there is improvement by US drivers.

With these future research efforts accomplished, we look forward to the day when metered roundabouts are widespread in the US, providing delay relief and allowing for the benefits of roundabouts to be enjoyed at many intersections.

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