Revisiting the Cycle Length—Lost Time Question With Critical Lane Analysis

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ABSTRACT

During oversaturation, a popular objective in traffic signal operations is to maximize throughput in order to keep traffic moving. As cycle lengths are increased, the proportion of "lost time" used to transition between signal phases is reduced. This is often a rationale for programming long cycle lengths into signal timing plans. To investigate the impact of cycle length, this paper revisits the concept of critical lane analysis to calculate throughput, and applies the technique to data collected at an oversaturated intersection in Indianapolis, Indiana. Traffic volumes were measured from over 10 weeks while different cycle lengths were tested at the intersection, ranging from 80 to 135 seconds. Somewhat surprisingly, during saturated conditions, no clear increase in the sum of critical lane throughput was observed, even when the cycle length increased by over 50%. In fact, there was a slight reduction in the total critical lane sum volume at 135 seconds. The findings concur with a recent study by Denney *et al*.. The decrease in throughput under the longer cycle lengths is attributed to the reduction of saturation flow during long green times. The paper discusses possible results of using a time-dependent saturation flow rate. Additionally, the critical lane analysis methodology may have applications for agencies to evaluate and rank intersections within corridors as under, near, or over saturation.

INTRODUCTION

During saturated conditions, capacity is a scarce resource, and a popular objective of signal operations is to make the best use of green time to maximize throughput. According to the signalized intersection capacity model of the *Highway Capacity Manual* (HCM), as cycle length increases, signals will allow greater throughput, because the proportion of "lost time" (phase clearance and start-up lost time) becomes an increasingly smaller proportion of the overall operating time, and traffic is assumed to flow at a constant saturation flow rate during green (*1*). Consequently, there is often a tendency to use longer cycle lengths during periods with high demand. This paper reports on observed throughput through the critical lanes at an intersection operating in saturated or oversaturated conditions during the afternoon peak hour. During the 10-week study period, while holding the percentage splits constant, various cycle lengths were tested, ranging from 80 to 135 s in order to ascertain the impact on intersection throughput.

ESTIMATING CAPACITY

The definition of capacity is the maximum amount of traffic that can flow through a travel lane during a given time, typically given in units of vehicles per hour. The HCM formula for the capacity of a signal-controlled lane is (*1*):

$$c_i = s\frac{g_i}{C}, \qquad \text{Equation 1}$$

where c_i is capacity (veh/h/lane) of phase i, s is the saturation flow rate (veh/h/lane), g_i is the amount of green time assigned to phase i, C is the cycle length (s). For simplicity, we assume that s is equal on all lanes. The relative importance of how the green time is allocated to each phase (i), is discussed in the next section.

CRITICAL LANE CONCEPT

At most intersections in the US, the dual-ring, eight-phase sequence is used, which allows for some flexibility in the timing of through and left turn phases. A typical ring diagram is shown in Figure 1. As indicated by the thick lines in this diagram, the *barriers* separate "mainline" phases {1,2,5,6} from "side street" phases {3,4,7,8}. The controller is required to concurrently terminate phases ending at a barrier, before moving on to the other block of phases. Because of this, a signal could be considered to be at capacity even if there is only demand for phases in one ring. For example, in Figure 1, if there is heavy demand for phase 2, but light demand for phase 6, the controller will still need to remain in the {2,6} state until it is released from serving phase 2. For this reason, it is rather misleading to calculate throughput by summing the volume across all lanes at the intersection. A better option is to consider the volume passing through the *critical lanes*, or those for which the demand (or more specifically, the volume-to-saturation flow ratio) is heaviest. The phases controlling movements from these lanes are called the *critical phases.*

The critical lane / critical phase concept is central to the computation of intersection capacity utilization in the HCM. The 1985 version of the HCM included a planning application worksheet to estimate intersection capacity utilization, as shown in Figure 2. The worksheet succinctly demonstrates the critical path concept. Of the eight through and left-turn movements existing at the intersection, we find the maximum volume (in veh/h/lane) of a given through phase and its opposing left turn, for both streets. The sum of these critical volumes reflects the overall capacity need of the intersection. Figure 3 interprets the critical lane concept in the dual-ring, eight-phase paradigm. Here, the four possible "critical paths" in the ring diagram are illustrated. To compute the critical lane throughput (T) at an intersection, the maximum volume on the critical path should be summed. In the eight-phase, dual-ring context the formula would be as follows:

$$T = \frac{1}{n_L} \max\{(v_1 + v_2, v_5 + v_6\} + \max\{(v_3 + v_4), (v_7 + v_8)\},$$ Equation 2

where v_i is the volume of phase i in veh/h/lane and n_L is the number of lanes in the critical path. If instead we were to sum across *all* lanes at the intersection, we would underestimate the overall utilization of intersection capacity. For example, in the extreme case that all phases in ring 1 (phases 1,2,3,4) are saturated, while those in ring 2 (phases 5,6,7,8) have no demand, we would compute that the intersection is half-loaded, but the reality would be that the *critical* phases are in fact fully loaded, and effectively the intersection would have no capacity to spare (other than possibly changing the use of some lanes).

Equation 2 relies on an assumption that flow characteristics among the possible critical paths are similar enough that the possible values of throughput for alternative critical paths are comparable. At many intersections this is perhaps not an unreasonable argument (e.g., phases 3 and 8 would together have the same potential throughput as phases 4 and 7). However, some configurations might make the assumption tenuous (*e.g.*, one left turn is protected only and the opposing left is protected-permitted; the intersection geometry is highly asymmetric; etc.).

The theoretical critical lane capacity is equal to

$$c = s\sum_{i\in CP}\frac{g_i}{C} = s\sum_{i\in CP}\frac{S_i - Y_i - R_i}{C} = s\frac{(C-L)}{C}, \qquad \text{Equation 3}$$

where CP is the set of critical phases, S_i is the split time of phase i, Y_i is the yellow time of phase i, R_i is the red clearance time of phase i, and L is the total *lost time* used in the critical phases.

Equation 3 predicts intersection capacity as a function of cycle length C and lost time L. Figure 4 shows theoretical curves using saturation flow rate s = 1900 veh/h/lane with several different quantities of L. All of the curves asymptotically approach s. Within the range of typical cycle lengths, Equation 3 clearly shows that longer cycle lengths are associated with greater capacity (and therefore throughput), especially with larger values of L, which are typical at intersections with more phases or wider crossing distances. For example, for L = 20, if C = 100, approximately 1525 veh/h/lane is expected, while increasing C to 140 is predicted to increase the capacity to 1625 veh/h/lane.

This analysis, of course, relies on the assumption that traffic passes through the intersection at a *constant* saturation flow rate during saturated conditions. Traffic engineers have qualitatively reported seeing actual discharge rates decreasing as green times extend beyond 30 seconds or so (*6*). Most of the existing literature on saturation flow presents data relevant to the discharge of rather short queues of 10 or fewer vehicles (19 seconds of green at 1900/veh/h). However, a handful of studies have examined the dynamics of saturation behavior in longer queues under longer green times:

- Teply (*3*) examined saturation flow rates and found that saturation flow reached its maximum around 40 seconds into green, beyond which it decreased.
- Li and Prevedourous (*4*) reported saturation flow with respect to queue position and found that, for through movements, the flow rates reached their maximum at approximately the twelfth vehicle in queue, gradually decreasing thereafter.
- Khosla and Williams (*5*) examined headway with respect to vehicle position at several intersections, and found a gradual increase in saturation headways and a reduction in flow after approximately 40-50 seconds of green.
- Denney *et al*. (*6*) examined headway with respect to queue position, and found that it gradually increased for vehicles further back in queue, with varying behavior by lane. The behavior became less deterministic after approximately the 30th vehicle in queue. Because of strong differences in behavior by lane, the increase in headway was attributed to the impact of departing right-turning vehicles.

Denney *et al*. went further to examine the impact of cycle length on throughput in simulation, finding that using a shorter cycle length resulted in slightly increased throughput as the intersection entered the saturated regime. The results suggest that increasing the cycle length might actually be counterproductive if the objective is to maximize throughput.

This paper seeks to empirically determine whether the relationship between cycle length and throughput can be observed at a congested real-world intersection over an extended period. Data obtained from 10 weeks of peak hour operation at an arterial traffic signal are used to directly measure throughput in the critical lanes at the intersection, with the empirical values compared to the theoretical curve.

DATA COLLECTION METHODOLOGY

Figure 5 shows the location and layout of the test intersection used for this study, US 36 (Pendleton Pike) and 56th Street in Indianapolis, Indiana. This intersection serves a commuter corridor linking Indianapolis to northeastern suburbs. During the PM peak, this corridor regularly becomes congested, and this intersection is a bottleneck, for several reasons. It is the first intersection with significant cross street traffic after a lane drop from three to two outbound through lanes. In addition, there is rather heavy outbound traffic making the eastbound left turn from 56th Street onto northbound US 36 (phase 7). Furthermore, during the study period, road construction on a parallel freeway diverted outbound traffic from Indianapolis to both US 36 and 56th Street, further increasing the amount of traffic at the study intersection.

High resolution detection and phase events were logged on a standard actuated controller (*7*). Vehicle counts were obtained from the intersection using loop detectors with count amplifiers. This automatic vehicle counting technique has been used extensively in Indiana (*8*) and elsewhere (*9*) for several years. Detection zones are shown in Figure 5. Vehicles departing from approaches 56th Street are counted by stop bar detectors, while the approaches on US 36 are counted from advance detectors. The outbound approach (phase 2) features a right-turn lane without a dedicated counting detector. Because traffic on this movement is able to enter the lane from very far back and can nearly always proceed through the intersection without stopping, this lane has been ignored in the analysis. Because of the heavy skew of the intersection, the left turns from the mainline are prohibited. Consequently, there are only six phases at the intersection.

Phase timing data pertaining to this intersection is provided in Table 1. During the study, six different cycle lengths ranging between 80 and 135 seconds were tested at the intersection over the course of 10 weeks. For each cycle length, the *percentage* splits were kept the same, with the resulting second splits and expected green times in Table 1. With the mainline through movements (phases 2 and 6) having a split of 55%, the expected green times are generally quite long. During saturated conditions, the side-street phases usually do not gap out, but the handful of occurrences taking place within the time period result in slightly longer green times for phases 2 and 6 than shown in Table 1.

Table 2 explains the timetable during which various test cycle lengths were deployed at the intersection. During the week of May 21, 2012, a different cycle length was tested at the intersection for each day in the week. Over the next four weeks, the baseline plan (C = 100 s) was in operation. Beginning from June 25, 2012, a different cycle length was tested at the intersection every week, in order to assemble a larger number of samples. The count of vehicles was tracked for the six phases by analyzing the high-resolution controller data (*10*). Vehicle counts from the most congested operating hour (16:30–17:30) were tabulated from day to day and used to calculate the throughput on the critical phases, using Equation 2. The critical phases at the intersection were {2, 7, 8} throughout the study, because of the consistent dominance of traffic leaving Indianapolis on phases 2 and 7 (see Figure 5).

RESULTS

Observed Throughput versus Cycle Length

Figure 6 shows the critical phase throughput by date during the study period. This view shows that there was some stochastic variation in the throughput from one day to another, but the average value is roughly the same at approximately 1400 veh/h/lane during the study period. One exceptional date in the analysis period is the holiday on July 4, where traffic levels were very low and clearly not congested.

Figure 7 shows daily throughput values plotted against cycle length. The symbols indicate the weeks during which the data was collected. In addition to the observed values, the theoretical curve is included, as generated using s = 1900 veh/h/lane and the lost time in the critical phase group {2, 7, 8} L = 20.1 s. Finally, the 1985 HCM thresholds of 1200 and 1400 veh/h/lane are highlighted. The averages and standard deviations of the clusters of observations at the trial cycle lengths are presented in Table 3 and are compared with the theoretical curve in Figure 8. The July 4 data is excluded from these computations.

The results suggest that throughput does not monotonically increase with cycle length, as anticipated by the theoretical curve. Instead, the throughput ranges from 1341-1435 veh/h/lane, with relatively small standard deviations (less than 5% of the mean) for all tested cycle lengths. The highest throughput occurs at 100 s. The upper and lower ends of the cycle length range have the lowest throughputs, with C = 135 surprisingly having less throughput than C = 80. Even if these bounding cases are ignored, the results nevertheless indicate that moving from, say, 100 to 120 seconds is not shown to substantially increase throughput. Instead, it appears to lower it.

These results agree with a recent simulation study by Denney *et al*. (6), where a cycle length of 72 seconds yielded greater throughput than 177 seconds, which in turn had greater throughput than a cycle length of 270 seconds. The range explored in this paper is considerably smaller, but executed over a long time period during saturated conditions at a real-world intersection. Despite a > 50% increase in the cycle length (80 s to 135 s), there was no increase in throughput on the critical lanes. While this single-location study is not sufficient to characterize a *general* relationship between throughput and cycle length, the results further confirm recent findings, and suggest a research need to better characterize the phenomenon. In particular, Denney *et al.* attributed the reduction in saturation flow to departing turning vehicles entering turning lanes. Additional observations would be needed to characterize the impacts of turning lanes and other factors on the relationship between saturation flow rate and green time.

Apart from the throughput performance of the intersection across different cycle lengths, the critical lane methodology might additionally be useful for evaluating and ranking the level of utilization at intersections across a system to identify where intersections are under, over, or near capacity (Figure 2), as well as a means of identifying the potential impacts of lane additions or closures for planning purposes.

Investigating the Saturation Flow Assumptions

The existing capacity model (Equation 1) is rather simplistic in its assumption that s is a constant rate that occurs during oversaturation. Although in this paper we have not measured individual headways, the resulting throughput—cycle length relationship offers an opportunity to consider possible alternative models that might better explain the trend. In approaching this problem, we ask the question: What would happen to the theoretical throughput if s is made to be a time-varying function, $s(t)$? The purpose of the following discussion is not to seek out a specific form for a new model, but rather to explore possible outcomes should further research be carried out to find such a model.

Figure 9 shows the differences in the relationship between capacity and green time for three different potential capacity formulas. In the current model (Equation 1) , s is a constant (s_0), meaning that capacity increases linearly with green time. Another possibility is that s exponentially decays with time—indicated by the "exponential" line for the function $s(t) = s_0e^{kt}$. The slope of this curve becomes smaller and smaller, indicating that the marginal increase in capacity becomes less and less, containing a sort of law of diminishing returns. Another possibility is a linear function $s(t) = s_0 + kt$. The form of this function is conceptually simpler, and similar to the exponential formula within the range of likely green times. However, at green times above approximately 100 seconds, s becomes negative, and the formula is no longer valid (indicated by the dashed line).

The total capacity (and thus the expected throughput at saturation flow) is calculated by summing the flow rate during the green time—which is equivalent to the following statement:

$$c = \frac{C-L}{C}\int_0^g s(t)dt \quad , \qquad \text{Equation 4}$$

For example, if s is constant, the formula is simply $c = s_0 \dfrac{C-L}{C}$, the same as Equation 3.

Figure 10 shows the resulting throughput when some possible alternative formulas are used, in comparison with the current HCM model where $s = s_0$, and the empirical data from the study. The exponential and linear models both *attain a maximum throughput* around approximately C = 100 (with a very broad range of "good" solutions), unlike the constant s curve where throughput increases monotonically with cycle length. The variable s curves also do a better job of anticipating the reduction of throughput at 135 seconds, unlike the constant s curve.

In closing, we emphasize that this discussion is not intended to suggest actual $s(t)$ formulas, but instead presents two mathematically simple forms yielding throughput curves that do not monotonically increase with cycle length. Accurate models of $s(t)$ would require considerably more data collection to develop, and are beyond the scope of this paper. However, the two basic curve shapes explored in this informal analysis suggest that if $s(t)$ was well-known, it would be possible to develop a model for optimizing cycle length for throughput during saturated conditions. Techniques for measuring traffic flow characteristics investigated elsewhere by Remias *et al*. (*11*) would make it possible to automatically collect data to characterize $s(t)$ at a number of intersections spanning a variety of conditions.

CONCUSIONS

This paper used critical lane analysis (Figure 2) to analyze 10 weeks of field collected data (traffic counts by movement during congested peak hour operations) under several cycle lengths ranging from 80 to 135 seconds. The throughput on the critical path of the test intersection was found to stay at around 1400 veh/h/lane regardless of which cycle length was used (Figure 6, Figure 7). This finding is contrary to a common expectation that throughput increases monotonically with cycle length. In fact, there was a slight *decrease* in the observed throughput at the longest cycle length of 135 seconds.

The observations suggest that commonly accepted theoretical models of capacity, such as the HCM model, in which saturation flow rate is presumed to be constant, do not accurately reflect saturation flow under longer green times that occur during long cycle lengths. The reduction of saturation flow in long green times has been reported in several other studies (*3,4,5,6*). The reduction in total intersection throughput agrees with the recent simulation study by Denney *et al*. (*6*). A brief discussion of potential alternative models was presented to explore potential impacts of time-dependent saturation flow models. Future work to expand on this concept would require detailed observations of departure headways at many locations to understand how saturation flow rates vary with time. Additional work to determine the impact of cycle length on alternative operational objectives, such as queue length management, would also be desirable. As a stronger consensus is built on the capacity impact of cycle length, it would become easier to reconcile the relationship with progression objectives during non-saturated conditions (*12*).

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REFERENCES

1. *Special Report 209: Highway Capacity Manual*. Washington, D.C.: Transportation Research Board, 1985.
2. Day, C.M., D.M. Bullock, and J.R. Sturdevant. "Cycle-Length Performance Measures: Revisiting and Extending Fundamentals." *Transportation Research Record No. 2128*, pp. 48-58, 2009.
3. Teply, S. "Saturation Flow at Signalized Intersections Through a Magnifying Glass." Proc. Eighth International Symposium on Transportation and Traffic Theory, Toronto: Toronto University Press, pp. 145-162, 1983.
4. Li, H. and P.D. Prevedourous. "Detailed Observations of Saturation Headways and Start-Up Lost Times." *Transportation Research Record No. 1802*, pp. 44-53, 2002.
5. Khosla, K. and J.C. Williams. "Saturation Flow at Signalized Intersections During Longer Green Time." *Transportation Research Record No. 1978*, pp. 61-67, 2006.
6. Denney, R.W., E. Curtis, and L. Head. "Long Green Times and Cycles at Congested Traffic Signals." *Transportation Research Record No. 2128*, pp. 1-10, 2009.
7. Smaglik E.J., A. Sharma, D.M. Bullock, J.R. Sturdevant, and G. Duncan, "Event-Based Data Collection for Generating Actuated Controller Performance Measures," Transportation Research Record, #2035, TRB, National Research Council, Washington, DC, pp.97-106, 2007.
8. Smaglik, E., Vanjari, S., Totten, V., Rusli, E., Ndoye, M., D.M. Bullock, and Krogmeier, J.V. "Performance of Modern Stop Bar Loop Count Detectors over Various Traffic Regimes," Transportation Research Board, TRB, National Research Council, Washington, DC, Paper No. 07-1090, 2007.
9. "Using Existing Loops at Signalized Intersections for Traffic Counts: An ITE Informational Report," *ITE Journal*, Vol. 78, No. 2, February 2008.
10. Day, C.M. *Performance-Based Management of Arterial Traffic Signal Systems.* PhD Thesis, Purdue University, May 2010.
11. Remias, S.M., A.M. Hainen, G.M. Grimmer, A.D. Davis, C.M. Day, T.M. Brennan, and D.M. Bullock. "Leveraging High Resolution Signalized Intersection Data to Characterize Discharge Headway Distributions and Saturation Flow Rate Reliability." Proc. Transportation Research Board Annual Meeting, Paper No. 12-2122, 2012.
12. Shelby, S.G., D.M. Bullock, and D. Gettman. "Resonant Cycles in Traffic Signal Control." In *Transportation Research Record No. 1925*, Transportation Research Board of the National Academies, Washington, DC, pp. 215-226, 2005.

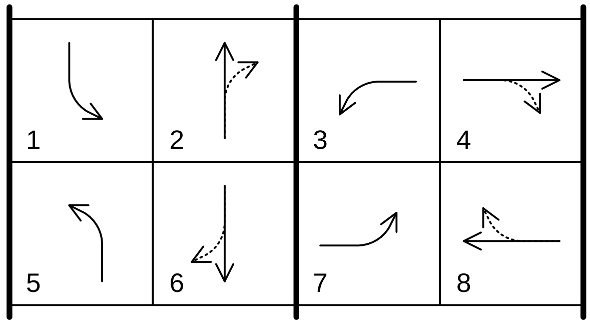
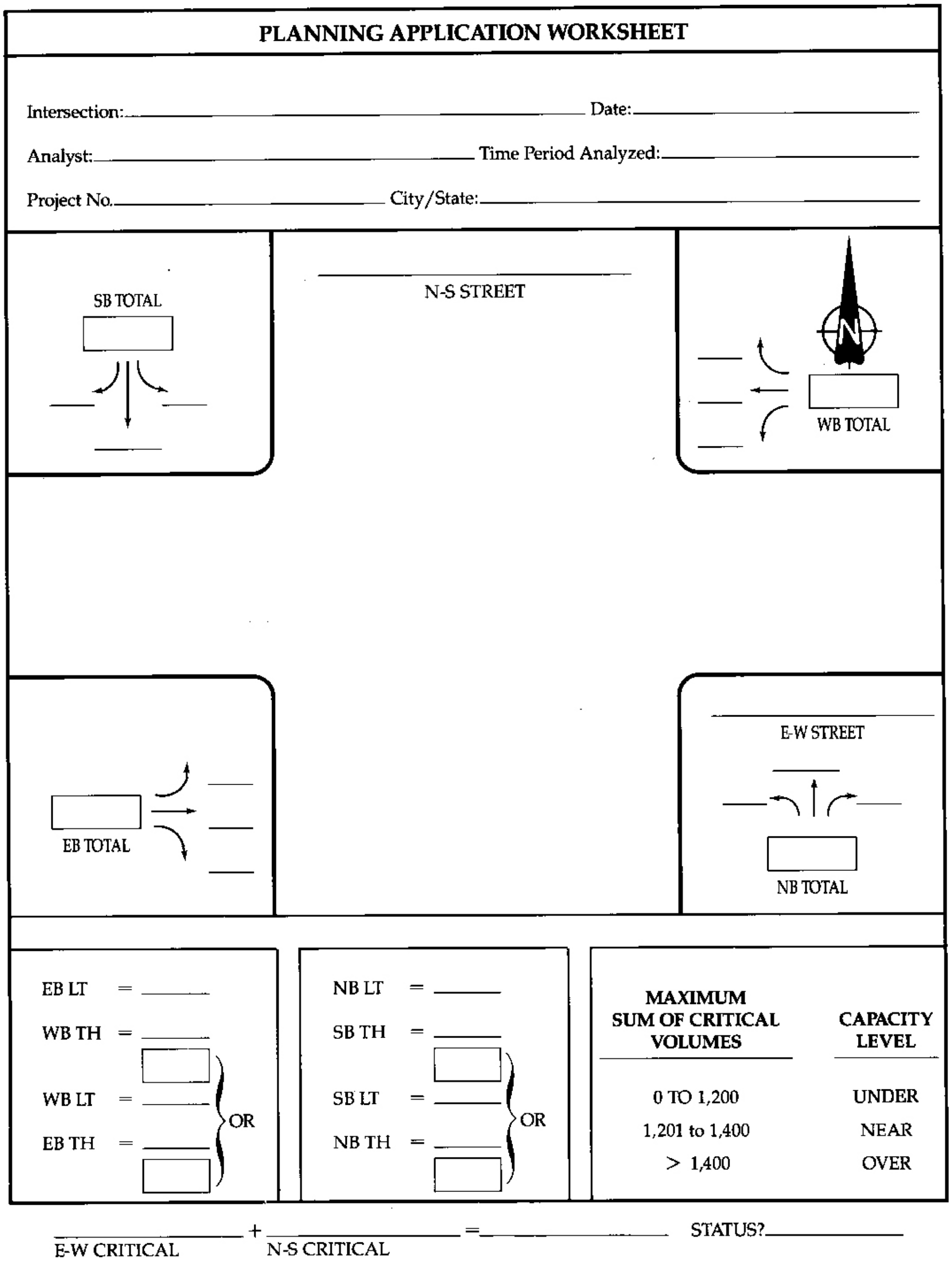


Figure 1: Typical dual-ring, eight-phase configuration.



PLANNING APPLICATION WORKSHEET

Intersection: ______ Date: ______

Analyst: ______ Time Period Analyzed: ______

Project No. ______ City/State: ______

SB TOTAL

N-S STREET

WB TOTAL

EB TOTAL

E-W STREET

NB TOTAL

EB LT = ______
WB TH = ______
WB LT = ______
EB TH = ______
OR

NB LT = ______
SB TH = ______
SB LT = ______
NB TH = ______
OR

MAXIMUM SUM OF CRITICAL VOLUMES	CAPACITY LEVEL
0 TO 1,200	UNDER
1,201 to 1,400	NEAR
> 1,400	OVER

______ + ______ = ______ STATUS? ______
E-W CRITICAL N-S CRITICAL

Figure 2: Planning Application Worksheet, from the 1985 *Highway Capacity Manual* (1).

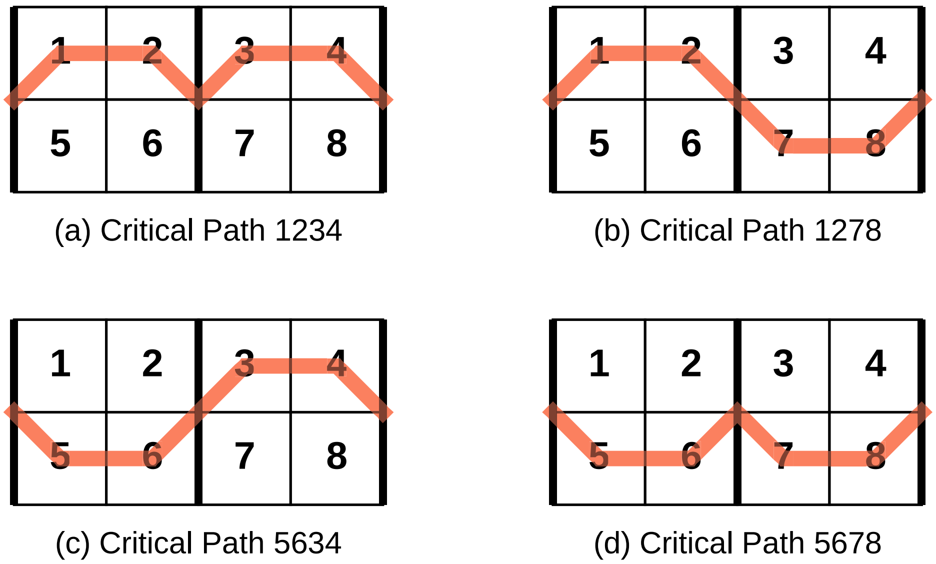


Figure 3: Possible critical paths in the dual-ring eight-phase controller sequence (2).

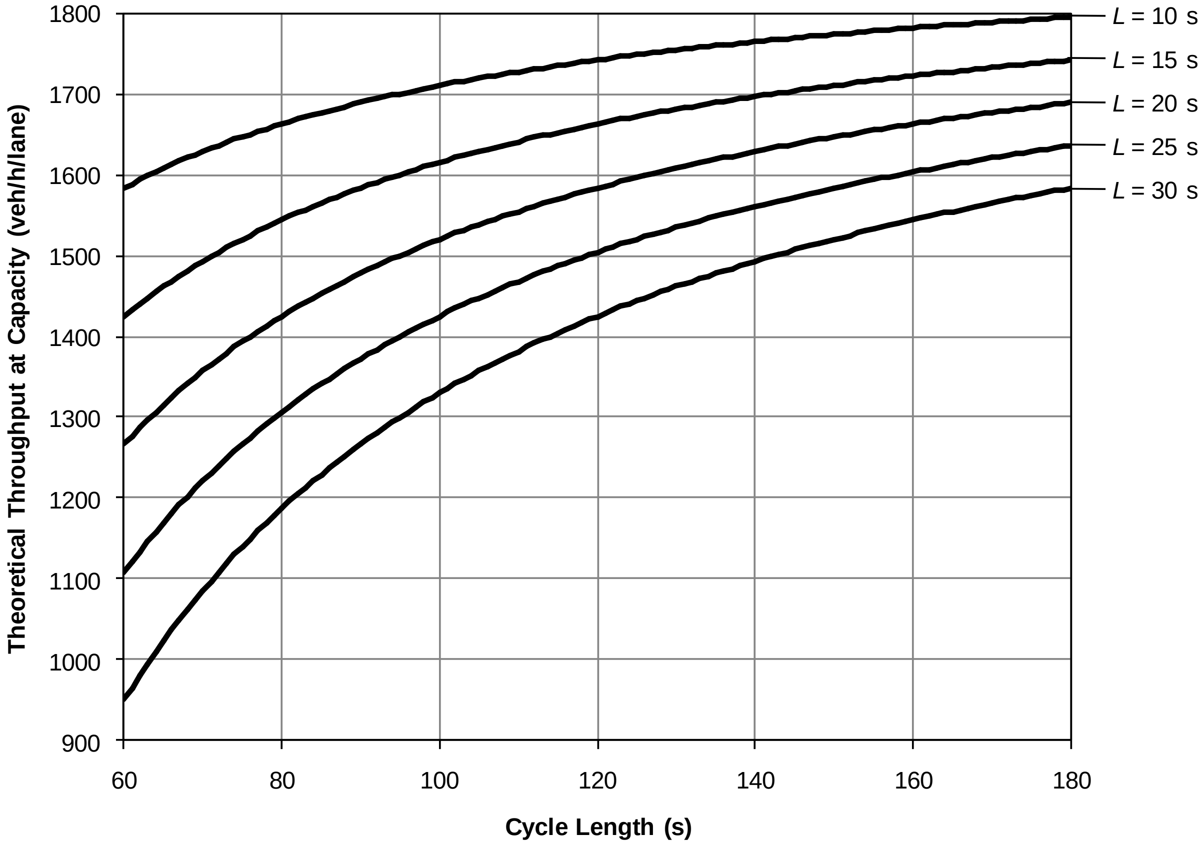


Figure 4: Theoretical throughput versus cycle length, different total lost time values (using s = 1900 veh/h/lane).

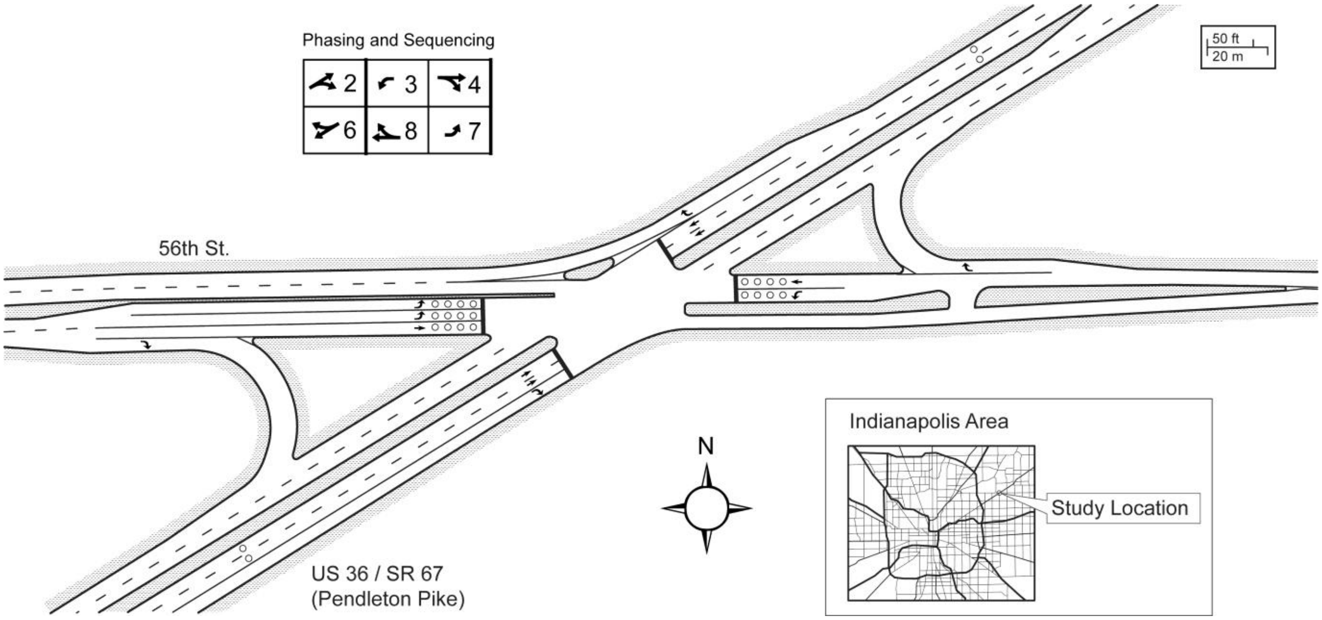


Figure 5: Layout of the test intersection.

Table 1. Phase Timing Data.

Phase	**2**	**3**	**4**	**6**	**7**	**8**
Minimum Green (s)	15.0	5.0	7.0	15.0	5.0	7.0
Yellow Clearance (s)	4.7	4.0	4.0	4.7	4.0	4.0
Red Clearance (s)	2.5	3.3	2.9	2.5	2.9	2.0
Total Clearance (s)	7.2	7.3	6.9	7.2	6.9	6.0
Percentage Split	55%	15%	30%	55%	30%	15%
Split Time (s), $C = 80$	44.0	12.0	24.0	44.0	24.0	12.0
$C = 95$	52.3	14.3	28.5	52.3	28.5	14.3
$C = 100$	55.0	15.0	30.0	55.0	30.0	15.0
$C = 105$	57.8	15.8	31.5	57.8	31.5	15.8
$C = 120$	66.0	18.0	36.0	66.0	36.0	18.0
$C = 135$	74.3	20.3	40.5	74.3	40.5	20.3
Green Time (s), $C = 80$	36.8	5.0	17.1	36.8	17.1	6.0
$C = 95$	45.1	7.0	21.6	45.1	21.6	8.3
$C = 100$	47.8	7.7	23.1	47.8	23.1	9.0
$C = 105$	50.6	8.5	24.6	50.6	24.6	9.8
$C = 120$	58.8	10.7	29.1	58.8	29.1	12.0
$C = 135$	67.1	13.0	33.6	67.1	33.6	14.3

Table 2. Data collection timetable.

Cycle Length (s)	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Varied*	5/21 ($C = 120$)	5/22 ($C = 85$)	5/23 ($C = 95$)	5/24 ($C = 105$)	5/25 ($C = 135$)
100	5/28	5/29	5/30	5/31	6/1
100	6/4	6/5	6/6	6/7	6/8
100	6/11	6/12	6/13	6/14	6/15
100	6/18	6/19	6/20	6/21	6/22
80	6/25	6/26	6/27	6/28	6/29
135	7/2	7/3	7/4	7/5	7/6
120	7/9	7/10	7/11	7/12	7/13
105	7/16	7/17	7/18	7/19	7/20
95	7/23	7/21	7/22	7/23	7/24

* Different cycle lengths used each day during this week.

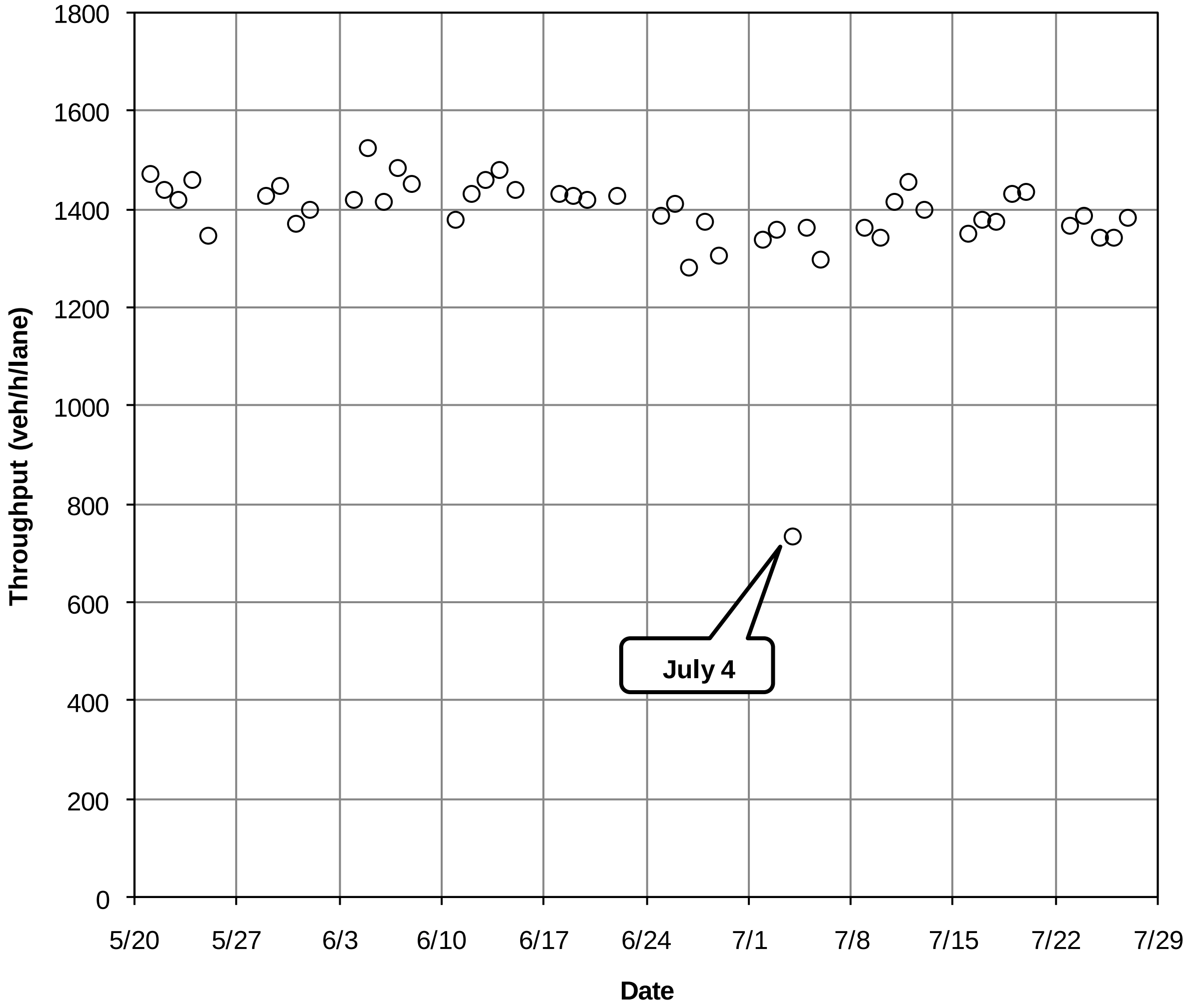


Figure 6: Critical movement throughput by date.

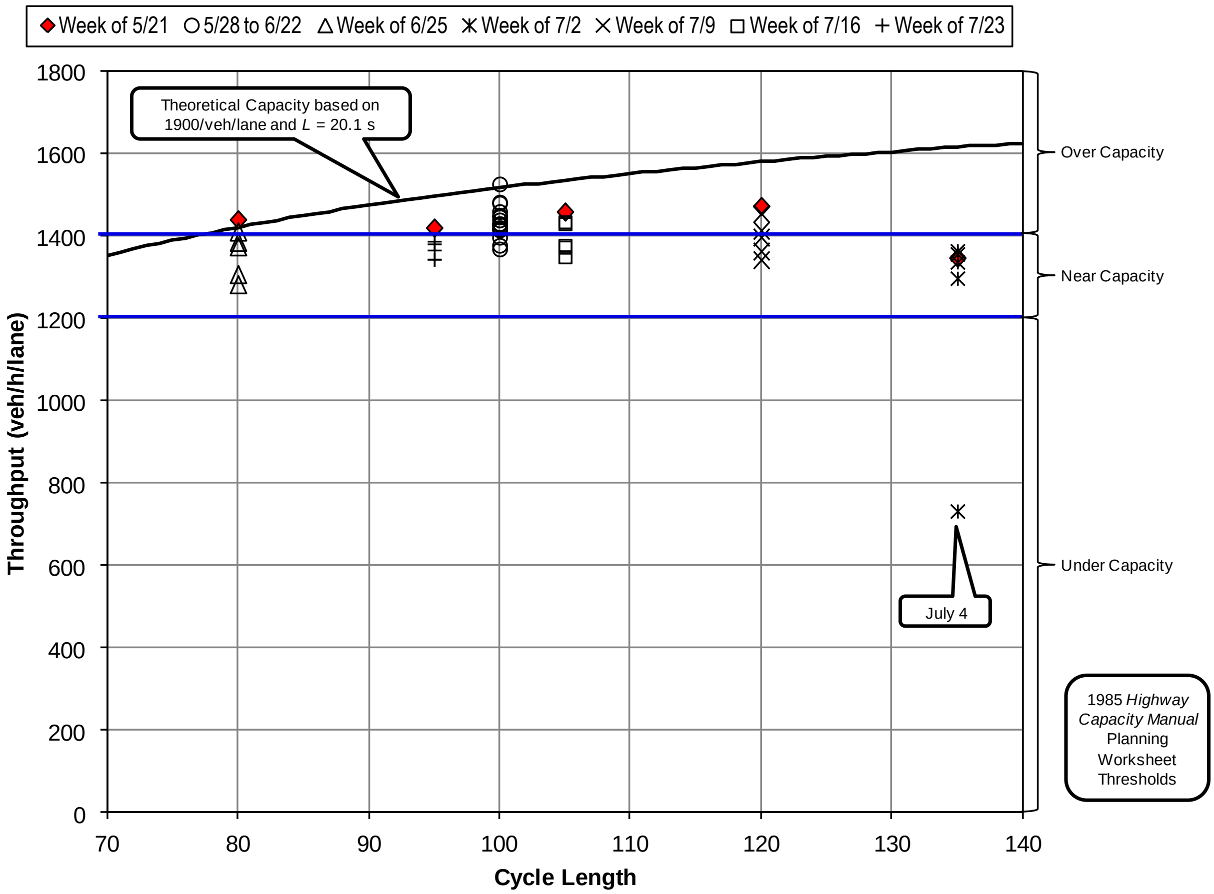


Figure 7: Raw data: Peak-hour throughput under different cycle lengths.

Table 3. Overall results: peak-hour throughput under different cycle lengths.

	Throughput (veh/h/lane)	
Cycle Length (s)	Average	Standard Deviation
80	1368	61
95	1374	29
100	1435	38
105	1405	43
120	1408	51
135*	1341	26

* Excluding data from 7/4/2012.

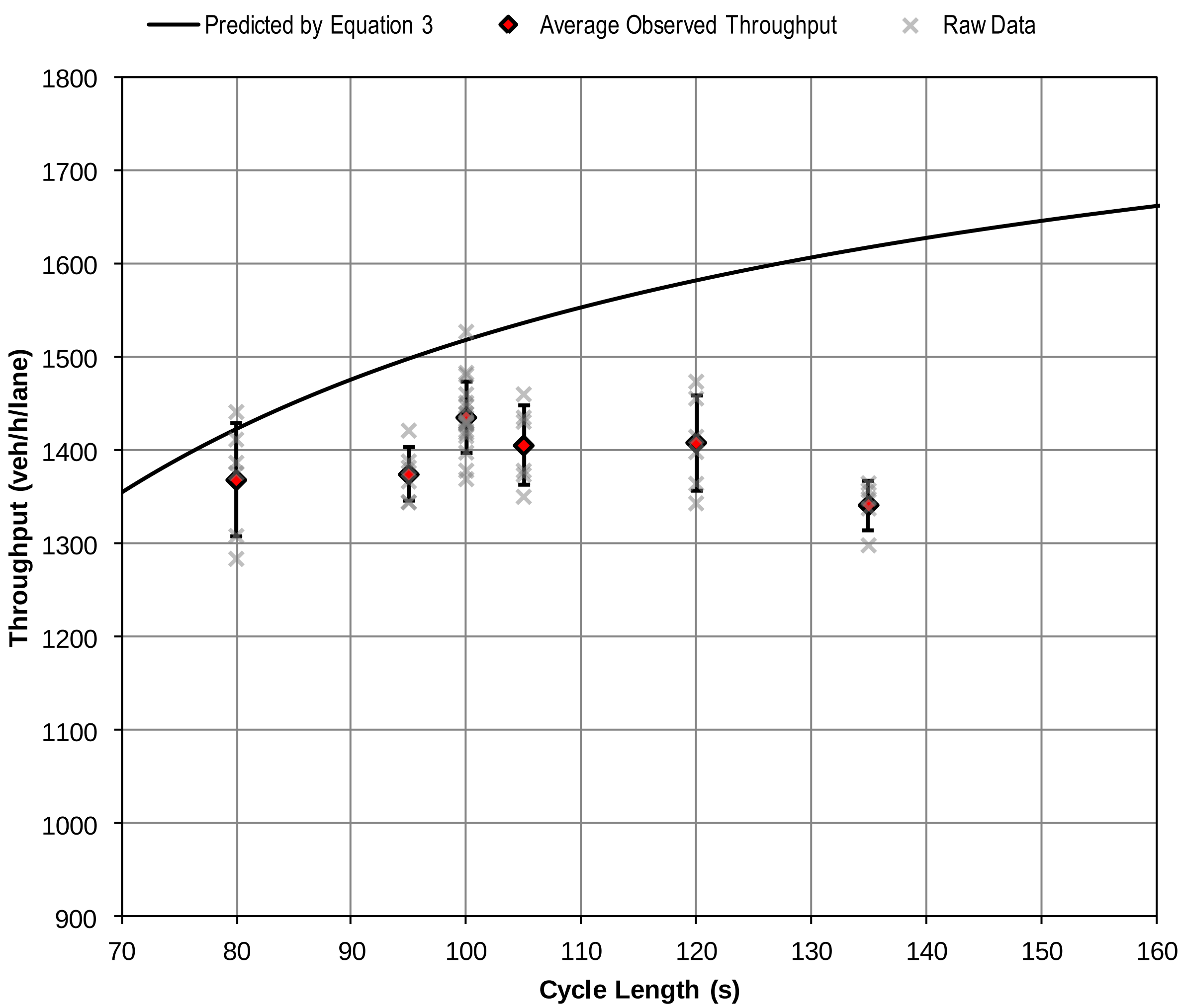


Figure 8: Average and standard deviation (error bars) of observed throughput, compared to the theoretical curve.

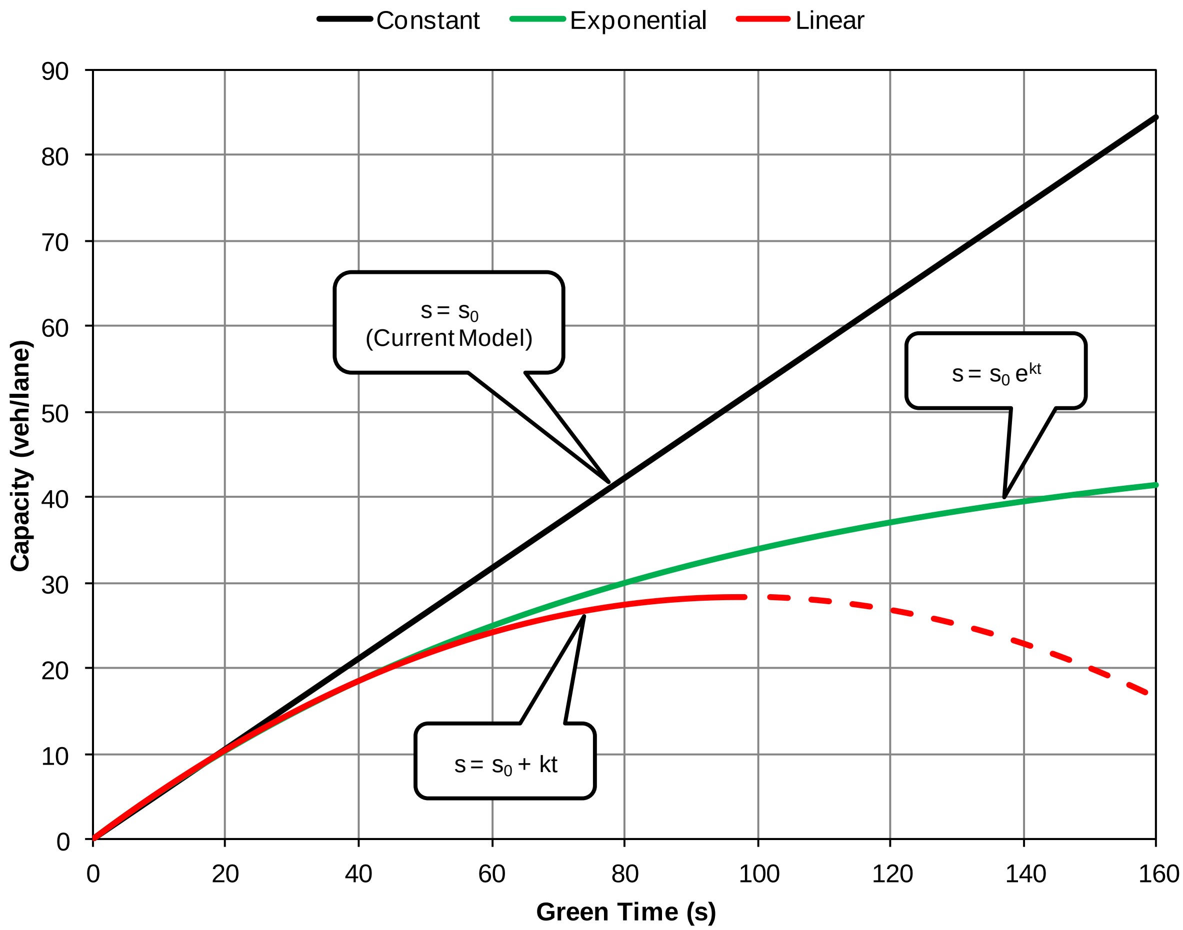


Figure 9: Possible alternative models of capacity based on time-varying saturation flow rates.

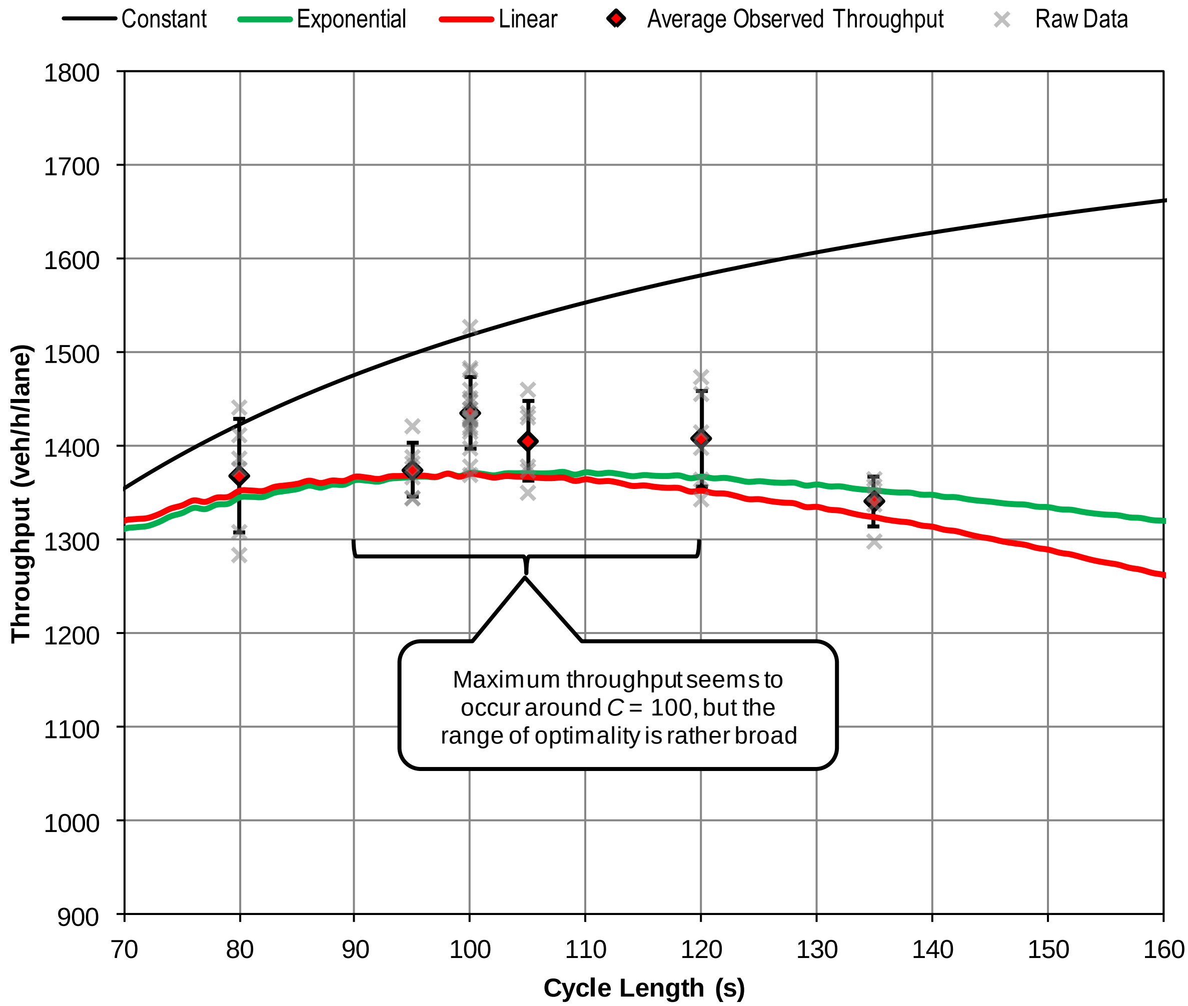


Figure 10: Potential impact of alternative capacity formulas. Error bars show standard deviation.