

MODELLING THE IMPACT OF SIDE-STREET TRAFFIC VOLUME ON MAJOR-STREET GREEN TIME AT ISOLATED SEMI-ACTUATED INTERSECTIONS FOR SIGNAL COORDINATION DECISIONS

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ABSTRACT

Signal coordination is generally recognized by traffic engineers as a beneficial strategy for improving arterial traffic progression and safety. Previous research on the criteria for establishing signal coordination plans has been focused on more objective factors such as intersection distance, arterial traffic volume, travel time, platoon dispersion and combinations of these factors. They provided useful guidance for signal coordination decisions, especially during peak hours. However, as traffic is usually less heavy during off-peak hours, the number of stops would have more influence on driver perception of traffic efficiency. This paper developed a mathematical relationship between arterial green time ratio and side-street traffic volume, which can serve as the theoretical foundation for determining signal coordination based on number of stops. The paper investigated how side-street traffic volume would affect major-street green time ratio when an isolated intersection is running semi-actuated signal operation. A probabilistic model was proposed to address this issue. The model was validated against simulation results and the upper limit of side-street traffic volume was defined for the model application. Following the proposed model, the paper briefly introduced how a traffic engineer can use the model results to make signal coordination decision based on the expected number of stops. A real case study was conducted. It was found that the model can successfully analyze the impact of side-street traffic volume on major-street green time at isolated intersections where left turns are permitted. The method for signal coordination decision can be adopted to determine the time periods of running signal coordination plans. The method and the results may be useful to traffic engineers for the effective management of traffic signal networks.

Keywords: Traffic volume, Green time ratio, Signal coordination, Number of stops, Probability

1 INTRODUCTION

2 Signal coordination has long been recognized as having beneficial effects on the quality of traffic
3 flow along a street or arterial (1-3). Good signal coordination can also generate measurable safety
4 benefits (4-6) and reduce emissions (7, 8). Despite the advantages of signal coordination, there
5 lack widely accepted standards in traffic agencies for when to implement signal coordination.

6 Various studies have been conducted regarding the criteria of establishing signal
7 coordination plans. Intersection distance has been recommended in manuals and research as a
8 criterion to support signal coordination decision, but these sources do not provide uniform
9 guidelines for agencies to determine whether coordination is necessary. The *Manual on Uniform*
10 *Traffic Control Devices (MUTCD)* provides the guidance that traffic signals within 800 meters (0.5
11 miles) of each other along a corridor should be coordinated unless operating on different cycle
12 lengths (9). The *Traffic Signal Timing Manual (STM)* states that when the intersections are in close
13 proximity and there is a large amount of traffic on the coordinated street, establishing coordination
14 would be easily justified (3). Besides considering intersection distance, traffic engineers may
15 develop their own standards on when traffic volume is substantially high to coordinate signals.

16 A number of simple criteria have been developed in previous research that do not directly
17 incorporate a platoon dispersion model to determine whether two intersections should be
18 coordinated. Robertson and Hunt (10) used *reduction in queue*, a function of travel volume and
19 travel time between intersections, as a coordination criterion. *The Traffic Signal Book* introduced
20 a criterion for coordinating signals considering both intersection distance and two-way peak hour
21 volume (11). When the ratio of two-way peak-hour link volume (vph) over link length (feet)
22 exceeds 0.5, the intersections should be coordinated. Chang and Messer developed the
23 *intercoordination desirability index* (12) incorporating factors such as travel time, traffic flow and
24 number of lanes, and recommended interconnection for two adjacent signalized intersections when
25 the index exceeds 0.35. These simple criteria can be adopted to guide signal coordination decisions.
26 They may also be employed to establish boundaries between sections of coordinated signals.
27 However, adopting these criteria may still result in conflicting recommendations, so engineering
28 judgment plays a significant role in real practice to determine signal coordination.

29 Some other research incorporated platoon dispersion models for the development of
30 coordination plans. Robertson integrated the concept of *delay minimization* with a formalized
31 platoon dispersion model (13). Manar and Baas (14) studied platoon dispersion under various
32 traffic volumes. Their study provided evidence for signal coordination needs during peak hours
33 and suggested that further study is necessary for signal coordination decision during off-peak hours.

34 Simulation is often used to determine coordination requirements and benefits, particularly
35 when performed in connection with retiming of traffic signals (15). Traffic engineers may employ
36 a general model such as CORSIM and VISSIM, together with a signal timing program, or may use
37 the optimization features of a signal timing program such as Synchro/SimTraffic. In the latter case,
38 coordination requirements and section boundary identification may be directly coordinated with
39 the signal retiming effort.

40 Typically, signal optimization software minimizes the total delays and the number of stops
41 at intersections along the subject arterial street. Using delay and number of stops is a more
42 perception-based approach to coordination design compared to the aforementioned methods. A
43 research report (16) specifically documented *number of stops* as a criterion for good coordination
44 plans used by Indiana Department of Transportation. It stated that an arterial signal plan is
45 acceptable when traffic progression along the arterial is reasonably smooth and most of the drivers
46 moving along the arterial street do not stop at two consecutive intersections. Based on the
47 probability of making a certain number of stops, a model was proposed to determine when to turn
48 on signal coordination plans and the relationship between green time ratio and traffic volume was

assessed using simulation tools (17). However, to the authors' best knowledge, no such research has established a direct relationship between traffic volume and green time ratio on an arterial. Therefore, coordination decisions based on number of stops may use more valid theoretical evidence.

When traffic is usually less heavy during off-peak hours, number of stops would have more influence on driver perception of traffic efficiency. This is the basis for engineers using number of stops as a criterion to determine whether to implement signal coordination during off-peak hours. This paper aims to develop a mathematical relationship between arterial green time ratio and side-street traffic volume, which can serve as the theoretical foundation for determining signal coordination based on number of stops, especially during off-peak hours.

The remaining of this paper is organized as follows. Problem statement and model assumption are provided in the next section. A probabilistic model is then proposed to address how side-street traffic volume will affect the green time ratio of an arterial street at an isolated semi-actuated intersection. The model validity is tested against simulation results and the upper limit of side-street traffic volume is defined for the model application. Sensitivity analyses are also included and the critical parameters are identified. Following the proposed model, the paper briefly introduces how a traffic engineer can use the model results to make signal coordination decisions. The summary and conclusions are provided in the end.

PROBLEM DESCRIPTION AND ASSUMPTIONS

During off-peak hours, especially at low volume conditions, signalized intersections (with an arterial street and a side street) can run semi-actuated signal operation. Detectors are placed at the minor approaches, which usually include side-street movements and in some cases the major-street left-turn movements. Green time will remain on the major-street through movements unless there is demand for the minor movements. A minor movement is served only when a vehicle demand of that phase is detected. When this phase is in service, it retains the right of way for a *minimum green* time and additional time can be given in the form of *passage time* if more vehicles are detected. If there is enough traffic, extensions will be added to the phase up to some set *maximum green* time. However, if another call is not received during the green time, the phase will gap out. Under this semi-actuated operation, the green time of each minor-movement phase depends on the detected demand of that movement. Because there is no detection for major movements, the green time of major movements is also determined upon the minor-movement demand. In order to model the effect of side-street traffic volume on major-street green time, the following problem description is provided. Certain assumptions are made to mathematically develop the model.

Problem Description

At an isolated four-leg intersection, the signal is running semi-actuated operation without fixed cycle length. The traffic volume is at a relatively low level. Both the major street and the side street have their own minimum green time. The right-of way (green signal) will remain on the major street unless there is a demand from the side street. Side-street demand will be served after the major street reaches minimum green plus its yellow and all-red intervals.

The model is to calculate the major-street green time ratio under different volume scenarios.

Model Assumptions and Pre-defined Factors

The following assumptions are made so that the model can be mathematically derived.

- 1) The traffic demand on the two side-street approaches is combined. The major street vehicle arrival is independent from any upstream intersections and is considered random.

- 2) The basic model does not consider major-street left-turn phases, assuming that left-turn movements are permitted during major-street through-movement phases. The model only investigates semi-actuated intersections, so it is assumed that no detection is provided for the major movements. As a result, major-street traffic flow does not influence the major-street signal, so it is not modeled.
- 3) Major-street signal does not account for extension due to the assumption that no detection is available on major movements, as well as the configuration that green time is defaulted to remain on the major street.
- 4) Side-street signal accounts for green time extension. Side-street signal will run for the *minimum green* time and, if more demand exists, can extend in the form of *passage time* up to *maximum green*. Passage time is the maximum allowable headway (*MAH*) between two vehicles to extend the signal. It is necessary to point out that the terms *minimum initial* and *minimum green* are used interchangeably in some signal controllers. However, in this paper, minimum green equals the sum of minimum initial and passage time. (The *MAH* can be set to zero if no extension on the side street is considered.)
- 5) Because the analysis is only for low-volume conditions, it is assumed that side-street vehicle demand would not be sufficiently high to extend the signal to maximum green, so the model does not consider maximum green time for the side street.

Model Parameters

Based on the problem description and the above assumption, the following model parameters are defined.

- q_{minor} : side-street traffic volume (vph)
- $g_{\text{major_min}}$: major-street minimum green
- $g_{\text{minor_min}}$: side-street minimum green
- y_{major} : major-street yellow interval
- y_{minor} : side-street yellow interval
- ar_{major} : major-street red clearance (all red) interval
- ar_{minor} : side-street red clearance interval
- MAH : side-street passage time for signal extension
- R_{major} : major-street green time ratio

DEVELOPMENT OF A PROBABILISTIC MODEL

Side-Street Vehicle Time Headway Distribution

When side-street traffic volume is low, the vehicle arrivals are considered as random events. It is generally accepted in related research that, when platoon is not considered, the time headway follows an exponential distribution or a shifted exponential distribution if a minimum headway applies.

Time headway t follows Cowan's M2 distribution, as shown in Equation 1.

$$f(t) = \begin{cases} 0 & t < \Delta \\ \Delta \frac{q_{\text{minor}}}{3600} & t = \Delta \\ (1 - \Delta \frac{q_{\text{minor}}}{3600}) \frac{q_{\text{minor}}}{3600} e^{-\frac{q_{\text{minor}}}{3600}(t-\Delta)} & t > \Delta \end{cases} \quad (1)$$

where Δ ($\Delta \geq 0$) is the minimum safety headway. When Δ equals zero, Cowan's M2 reduces to an exponential distribution.

Basic Model Development for Intersections with Permitted Left Turns on the Major Street Cycle Length

Although no fixed cycle length applies under the semi-actuated operation, a cycle of the signal consists of three groups of intervals, including green time on the side street, green time on the major street, and the clearance intervals between green intervals. The cycle length is the sum of major-street green time, side-street green time and clearance intervals in between.

$$C_{\text{mean}} = G_{\text{mean_major}} + G_{\text{mean_minor}} + T_{\text{intergreen}} \quad (2)$$

Green Time Consumed by Side-Street

When side-street signal accounts for green extension, the side-street green time is the sum of minimum green and extended green time,

$$G_{\text{mean_minor}} = g_{\text{minor_min}} + G_{\text{ext}} \quad (3)$$

where G_{ext} is the mean green extension time.

Mean green time extension on the side street is calculated as

$$G_{\text{ext}} = -\frac{3600}{q_{\text{minor}}} + \left(\frac{\Delta}{1 - \Delta \frac{q_{\text{minor}}}{3600}} + \frac{3600}{q_{\text{minor}}} \right) \exp\left(\frac{q_{\text{minor}}}{3600}(MAH - \Delta)\right) - MAH \quad (4)$$

Then Equation 3 becomes

$$\begin{aligned} G_{\text{mean_minor}} &= g_{\text{minor_min}} + G_{\text{ext}} \\ &= g_{\text{minor_min}} + \left[-\frac{3600}{q_{\text{minor}}} + \left(\frac{\Delta}{1 - \Delta \frac{q_{\text{minor}}}{3600}} + \frac{3600}{q_{\text{minor}}} \right) \exp\left(\frac{q_{\text{minor}}}{3600}(MAH - \Delta)\right) - MAH \right] \end{aligned} \quad (5)$$

Green Time Consumed by Major-Street

The mean green time on the major street is calculated as

$$\begin{aligned}
G_{\text{mean_major}} &= (g_{\text{major_min}} + \frac{3600}{q_{\text{minor}}}) \cdot (1 - \Pr(t_{\text{minor}} \leq g_{\text{major_min}})) + g_{\text{major_min}} \cdot \Pr(t_{\text{minor}} \leq g_{\text{major_min}}) \\
&= (g_{\text{major_min}} + \frac{3600}{q_{\text{minor}}}) - \frac{3600}{q_{\text{minor}}} \cdot \Pr(t_{\text{minor}} \leq g_{\text{major_min}}) \\
&= g_{\text{major_min}} + \frac{3600}{q_{\text{minor}}} \cdot (1 - \Pr(t_{\text{minor}} \leq g_{\text{major_min}}))
\end{aligned} \tag{6}$$

with the probability of gap on side-street being less or equal to $g_{\text{major_min}}$

$$\Pr(t_{\text{minor}} \leq g_{\text{major_min}}) = 1 - (1 - \Delta \frac{q_{\text{minor}}}{3600}) \cdot \exp(-\frac{q_{\text{minor}}}{3600} \cdot (g_{\text{major_min}} - \Delta)) \tag{7}$$

Clearance Time Consumed between Green Intervals

Sum of clearance intervals is all the time intervals in between the major-street and side-street green time, calculated as in Equation 8.

$$T_{\text{intergreen}} = y_{\text{major}} + ar_{\text{major}} + y_{\text{minor}} + ar_{\text{minor}} \tag{8}$$

Major-Street Green Time Ratio

The major-street green time ratio is calculated as the mean green time on the major street over the mean cycle length,

$$\begin{aligned}
R_{\text{major}} &= \frac{G_{\text{mean_major}}}{C_{\text{mean}}} \\
&= \frac{G_{\text{mean_major}}}{G_{\text{mean_major}} + G_{\text{mean_minor}} + T_{\text{intergreen}}}
\end{aligned} \tag{9}$$

where $G_{\text{mean_minor}}$, $G_{\text{mean_major}}$, and $T_{\text{intergreen}}$ are shown in Equation 5, 6, and 8, respectively.

Upper Limit of Side-Street Traffic Volume for Model Application

The proposed model was to analyze the traffic operation under low volume condition, so we did not consider side-street queue discharge, which would happen when side-street volume is high. When the average queue discharge time is larger than or equal to the side-street minimum green time, the model no longer fits. Due to this fact, an upper limit of side-street traffic volume, q_{minor} , should be defined.

An estimation of average queue (measured in vehicles) when the side-street signal turns green is the average number of arriving vehicles when the side-street signal was yellow and red during last cycle,

$$Queue_{\text{avg}} = \frac{q_{\text{minor}}}{3600} (g_{\text{major_min}} + T_{\text{intergreen}}). \tag{10}$$

The queue discharge time is

$$T_{\text{dis}} = l_1 + \frac{Queue_{\text{avg}}}{s / 3600} \tag{11}$$

where l_1 is start-up loss time and s is the saturation flow rate.

Then the upper limit of q_{minor} is derived by

$$g_{\text{minor_min}} = T_{\text{dis}}$$

$$g_{\text{minor_min}} = l_1 + \frac{\frac{q_{\text{minor}}}{3600} (g_{\text{major_min}} + T_{\text{intergreen}})}{s / 3600} \quad (12)$$

$$q_{\text{minor}} = \frac{(g_{\text{minor_min}} - l_1)s}{g_{\text{major_min}} + T_{\text{intergreen}}}$$

In Signal Timing Manual (3), a practical estimation of start-up loss time and saturation flow rate is 2 sec and 1800 vph. Then the upper limit of q_{minor} can be estimated as

$$q_{\text{minor}} = \frac{(g_{\text{minor_min}} - l_1)s}{g_{\text{major_min}} + T_{\text{intergreen}}} = \frac{1800(g_{\text{minor_min}} - 2)}{g_{\text{major_min}} + 8} \quad (13)$$

The upper limit of side-street volume is a function of major-street and side-street minimum green. When the side-street volume exceeds the limit, it is not recommended to use the proposed model to evaluate the impact of side-street volume on major-street green ratio.

MODEL VALIDATION WITH SIMULATION RESULTS

A simulation model was developed using Python script to validate the proposed probabilistic model. The model generated a random vehicle arrival and simulated the corresponding signal operation process for a period of one hour under various volume scenarios. For each volume scenario, the simulation ran 100 times and the average major-street green time ratio was obtained. The results of the simulation model were compared to the calculated results from the proposed model to demonstrate that the proposed analytical model is able to represent the average major-street green ratio at semi-actuated intersections.

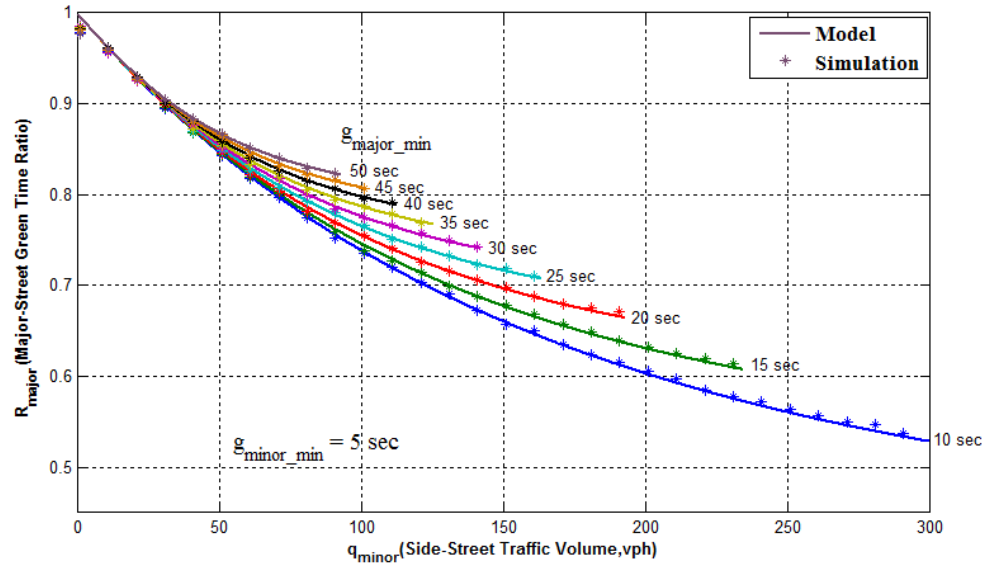


FIGURE 1 Comparison between Model and Simulation Results (Side-street vehicle time headway follows an exponential distribution).

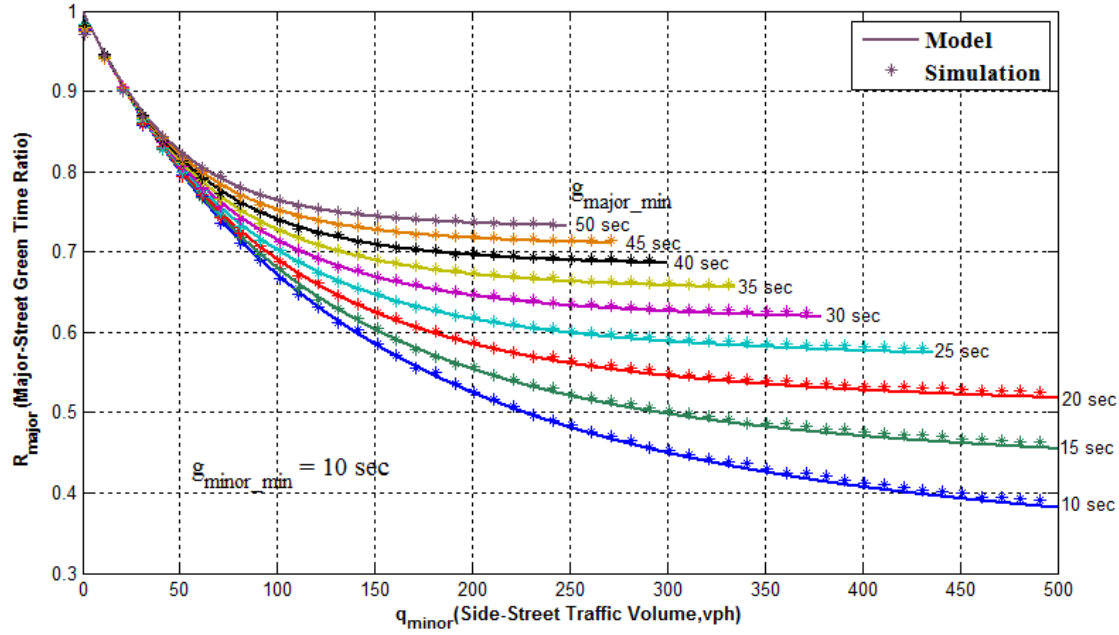


FIGURE 2 Comparison between Model and Simulation Results (Side-street vehicle time headway follows Cowan's M2 distribution).

Comparison between the proposed model and simulation results is provided. The scenarios of side-street vehicle time headway following both the exponential distribution (Figure 1) and Cowan's M2 distribution (Figure 2) were tested in the simulation. The range of side-street traffic volume tested in the simulation was from 1 to 500 vph. The derived upper limit of q_{minor} under each signal timing condition was also indicated in the curves. It can be concluded that the proposed model can appropriately estimate the major-street green time ratio under different side-street volume scenarios.

SIGNAL COORDINATION DECISION BASED ON THE PROPOSED MODEL

The proposed model established a relationship between side-street traffic volume and major-street green time ratio at an isolated intersection with semi-actuated signal operation. It provides a foundation for signal coordination decision based on number of stops.

If the signals on an arterial street of n intersections are running free (semi-actuated) and traffic volume is not high, the vehicle arrival is assumed as a random process. Thus, the probability of a major-street vehicle hitting a green light at an intersection equals the major-street green time ratio. Let p_i^g denote the probability of a major-street vehicle hitting a green light at intersection i , and let $(R_{\text{major}})_i$ denote the major-street green time ratio at intersection i . Then

$$p_i^g = (R_{\text{major}})_i. \quad (14)$$

When a vehicle travels along an arterial with n intersections, the probability of the vehicle making x stops ($0 \leq x \leq n$) can be calculated by

$$\Pr(X = x) = \binom{n}{x} \left[\prod_{j \in A} p_j^g \prod_{k \in B} (1 - p_k^g) \right] \quad (15)$$

where

A = a set of $(n-x)$ intersections where the vehicle arrives at green light,

B = a set of x intersections where the vehicle does not arrive at green light and stops.

If the major-street green time ratios of the intersections along the arterial are in close proximity, a good approximation of Equation 15 is a binomial distribution using the mean of p_i^g .

$$\Pr(X = x) = \binom{n}{x} (\bar{p}^g)^{n-x} (1 - \bar{p}^g)^x$$

$$\bar{p}^g = \left(\sum_{i=1}^n p_i^g \right) / n$$
(16)

Consequently, the probability of a vehicle making x or more stops when travelling on an arterial road with n signals operating free is determined as

$$\Pr(X \geq x) = 1 - \Pr(X \leq x-1) = 1 - \sum_{m=0}^{x-1} \binom{n}{m} (\bar{p}^g)^{n-m} (1 - \bar{p}^g)^m.$$
(17)

Signal coordination decisions can be made based on Equation 17. When the probability of making expected number of stops or more exceeds a certain value, signals should run coordination; otherwise the signals can run actuated control. In other words, when $\Pr(X \geq x) > K$, signals should run coordination. The application of this method requires two thresholds to be established. One is the number of stops (x), and the other is the probability of making expected number of stops (K).

As an example, Figure 3 depicts the probability of making 2 or more stops ($\Pr(X \geq 2)$) along an arterial with 4, 6, and 8 signals, with respect to various mean major-street green time ratio (\bar{p}^g). Assuming an arterial of 4 signals has a mean major-street green time ratio of 0.5, and the thresholds are established as $\Pr(X \geq 2) > 0.7$, the probability of a major-street vehicle making 2 or more stops being less than 0.7 will result in a decision not to run signal coordination.

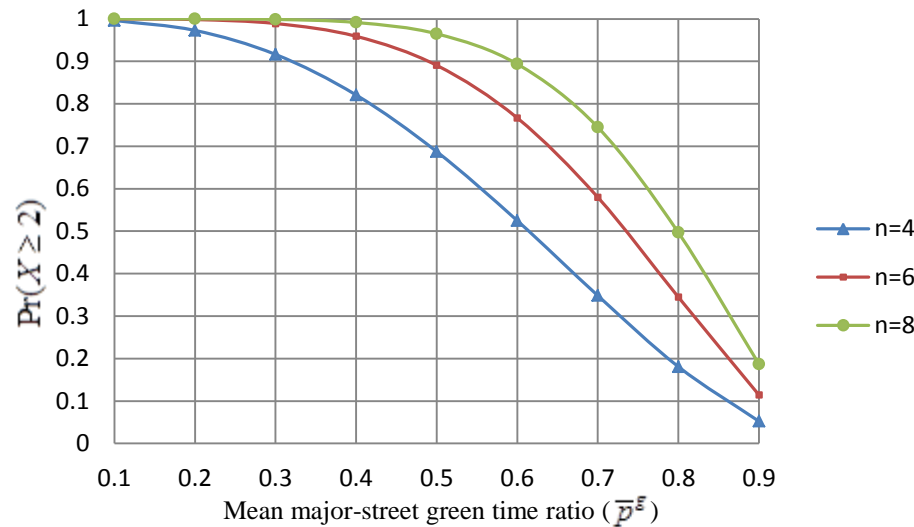


FIGURE 3 Probability of Making Two or More Stops along an Arterial

Case Study

A case study was conducted to demonstrate the application of the proposed model and signal coordination decision-making procedure.

Study Location

Fourth St (SR647) is one of the minor arterials in the city of Reno, Nevada that connects the Western and Eastern part of Reno. The study segment is a portion of the street in the downtown area with four signals. All of the four signals operate the way that matches the model assumptions. At each intersection, two major-street phases run concurrently with permitted left turns, and the same with two side-street phases.

Hourly side-street traffic volume can be obtained for two of the intersections, i.e. the intersections at Arlington and Ralston. The signal timing configurations required by the model for the two intersections are summarized in Table 1. The 24-hour volume profile is plotted in Figure 4.

TABLE 1 Basic Signal Timing Configurations at the Study Location

Intersection	Major-street minimum green (sec)	Major-street yellow interval (sec)	Major-street red clearance interval (sec)	Side-street minimum green (sec)	Side-street yellow interval (sec)	Side-street red clearance interval (sec)
4 th /Arlington	10	4	0.5	10	4	0.5
4 th /Ralston	5	3.5	0.5	5	3.5	0.5

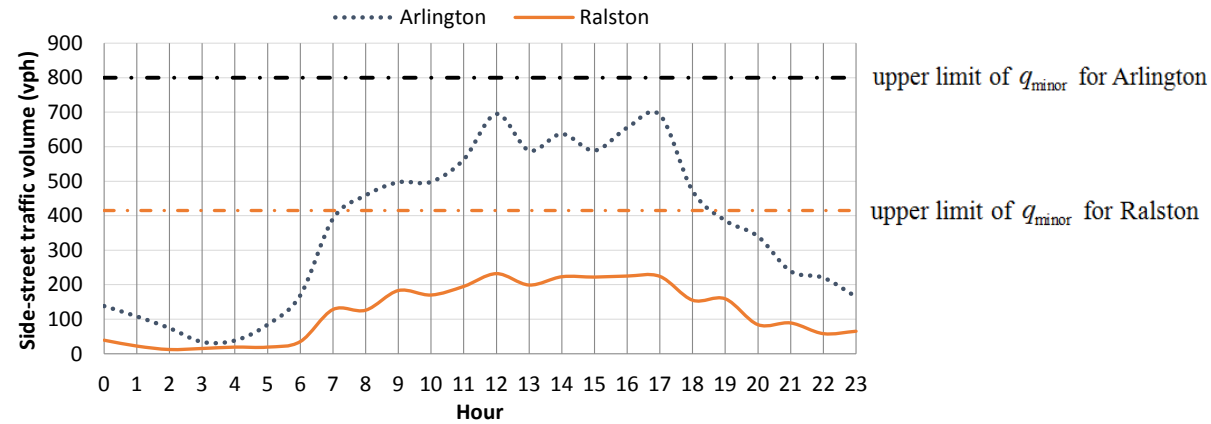


FIGURE 4 Side-Street Traffic Volume Profiles of the Two Intersections along SR647

Analysis and Signal Coordination Decisions

The signal coordination decision is based upon an established threshold. For the case study, the following to thresholds are considered in the analysis:

$$\Pr(X \geq 2) > 0.7$$

$$\Pr(X \geq 1) > 0.9$$

The first threshold describes the scenarios that more than 70% of the drivers make 2 or more stops along the study segment. The second threshold describes the scenarios that more than 90% of the drivers make 1 or more stops. Once the threshold is established, the associated cut-off point of \bar{p}^s can be obtained according to Equation 17. For the given case, the two associated \bar{p}^s values are 0.49 and 0.56, respectively.

The proposed model can produce the major-street green time ratio based on the traffic volume and basic signal timing parameters at each intersection. Both the major-street green time ratio (R_{major}) and the upper limit of side-street traffic volume (q_{minor}) need to be calculated.

Obtaining the upper limit of q_{minor} is used to verify if the model applies under the specific volume

condition. The upper limits of q_{minor} for the two intersections are indicated in Figure 4.

Ideally, data for each intersection along the study arterial should be collected and then the proposed model can be applied to obtain each R_{major} . Due to the limit of data availability, only two intersections have hourly traffic volume. For the demonstration of the decision-making procedure, the author assumed that the four intersections have close major-street green time ratios, and substituted the average of R_{major} at the two intersections for the average of all four intersections.

The resulting 24-hour \bar{p}^g and the two thresholds are illustrated in Figure 5.

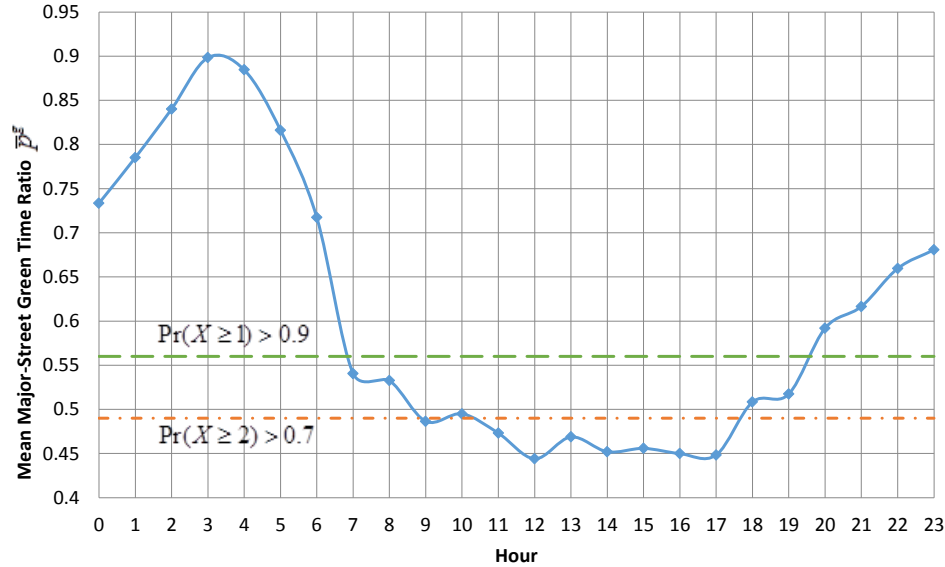


FIGURE 5 Hourly Mean Major-Street Green Time Ratio along the Study Segment if Signals Run Free

For the case study, the time periods when the signals should run coordination plans were determined based off Figure 5 and are summarized in Table 2.

TABLE 2 Recommended Time Periods to Run Signal Coordination Plan along the Study Segment

Threshold	Time period	
	Peak Hour (Run coordination)	Off-Peak Hour (No coordination)
$\Pr(X \geq 2) > 0.7$	8:45-17:45	0:00-8:45, 17:45-0:00
$\Pr(X \geq 1) > 0.9$	6:45-19:30	0:00-6:45, 19:30-0:00

SUMMARY AND CONCLUSION

The number of stops is one of the important criteria in signal optimization and has been adopted in some jurisdictions as a criterion for a good coordination plan. However, the factors that may impact number of stops have been researched less commonly in previous literature. This paper attempted to find the relationship between traffic volume and number of stops as the ground of signal coordination decisions.

The paper first developed a mathematical model to establish the relationship between side-street traffic volume and the probability of a major-street vehicle arriving at green at an isolated intersection where the signal is operating semi-actuated. The model was developed for

1 low traffic volume conditions, so the upper limit of side-street traffic volume for the model to
2 apply was derived. The model was validated against simulation results, and it can be concluded
3 that the model can appropriately evaluate the major-street green time ratio under low-volume
4 scenarios.

5 Based on the model, the probability of a major-street vehicle making a certain number of
6 stops or more was predicted by a probabilistic method. In order to determine the time periods for
7 coordination plans, two thresholds need to be established: the expected number of stops, and the
8 probability of expected number of stops. A case study was conducted for a minor arterials segment
9 with four signals, located in Reno, Nevada. The case study considered two criteria. One indicated
10 a lower tolerance of number of stops, and the other higher. It was found that a lower tolerance of
11 number of stops would lead to a longer period of signal coordination.

12 The decision-making method may be adopted by traffic engineers for the effective
13 management of traffic signal networks. The mathematical model proved a direct relationship can
14 be established between side-street volume and major-street green time ratio. However, this model
15 is limited to intersections where left turns are under permitted operation. If left turns are protected,
16 left-turn volume will also impact the through-movement green time. To apply the method in more
17 signal operation conditions, it is worthwhile to develop a model that accounts for protected left
18 turns. Discussion on this topic will be addressed in future studies.

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