A STOP BASED APPROACH FOR DETERMINING WHEN TO RUN SIGNAL COORDINATION PLANS

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ABSTRACT

This paper presents a stop based approach for determining when to run signal coordination plans based on the traffic volume. A stop based model is developed to predict the probability of making more than a certain number of stops while vehicles travel along an arterial during the actuated operation of signals. To determine when signals should go into coordination, two thresholds need to be established: the desired number of stops and the probability of desired number of stops. Through establishing the aforementioned thresholds, the level of traffic volumes in which coordination plans should be on are obtained. The application of the proposed model is showcased through a real case example study. Finally, a survey is conducted on when U.S. traffic agencies implement signal coordination plans. The results of the survey reveal that agencies use 250 vphpl up to 500 vphpl as a minimum level of traffic volume to trigger signal coordination plans. Considering the stop based model and the traffic volumes that these agencies use, it is revealed that the traffic agencies tend to establish a relatively low threshold for the desired number of stops.

Keywords: Signal coordination, traffic volume, stop based model, probability of stops
INTRODUCTION

Coordination of traffic signals is one of the traffic management tools to improve the performance of arterials in terms of traffic throughput and travel time. Nowadays, with the advancement of technology, signal coordination has to compete with other traffic signal control types such as adaptive traffic signal system and traffic responsive signal system, which are far more expensive. Therefore, the appropriate implementation of signal coordination plans that results in the maximal benefits prevent traffic practitioners from switching to the other traffic signal control systems. Despite the importance of signal coordination, most of traffic agencies have an opinion based on their experience about when to coordinate signals. For instance, they might be reluctant to coordinate signals when the distance between intersections is larger than one mile or when it is after 9:00 p.m.

The Traffic Signal Timing Manual recommends signal coordination when signals are in close proximity of each other and there is a large amount of traffic on coordinated streets (1). The Manual on Uniform Traffic Control Devices (MUTCD) states that traffic signals within 0.5 miles of each other should be coordinated (2). The Federal Highway Administration (FHWA) guideline recommends that when intersections are close together e.g., within 0.75 mile of each other, it is advantageous to coordinate them and at longer distances, the traffic volume and potential for platoon dispersion should be reviewed for coordination operations (3). It would be inferred from the manuals mentioned above that the discretion is given to the traffic engineer to determine when traffic demand is sufficiently high.

Several techniques have been developed over the years discussing when two adjacent signals should be coordinated. Yagoda et al. (4) introduced the idea of the coupling index (CI) which is a ratio of the link volume to the distance. The larger the index, the more desirable it is to coordinate two intersections. Later, their model was further developed by considering the distance squared, which is called the gravity model (5). Change (6) applied the idea of the interconnection desirability index to develop warrants, guidelines, and procedures to identify where the interconnection of signalized intersections should be implemented. The index combined traffic volume and platoon dispersion to measure the potential of isolated intersections for the interconnection. Synchro, the optimization and simulation software, uses the coordinatability factor (CF) to measure the desirability of coordinating intersections. This factor is a function of travel time, traffic volume, distance, vehicle platoon, vehicle queuing, and cycle length (7). Balke et al. (8) also developed guidelines and procedures for setting up a closed-loop traffic signal system. They provided procedures of when adjacent signals should be coordinated through the application of the interconnection coordinatability index. Hooks and Albers (5) studied the effectiveness of three different methodologies for determining the potential of coordination between two adjacent intersections. They compared the improved “coupling index”, “strength of attraction”, and the “coordinatability factor”. At the end, it was determined that none of these methods were effective, thus the engineering judgment and experience are the best tools to determine the potential for signal coordination.

Robertson (9) integrated the concept of delay minimization concept with a formalized platoon dispersion model. Manar and Baas (10) studied platoon dispersion over various traffic conditions from low to high volumes. Their study confirmed signal coordination during peak hours and they proposed further evaluation on signal coordination during off-peak hours. Andalibian et al. (11) developed a stop-base guideline recommending when to turn on signal coordination plans. Their guideline is a function of the number of signals and the average effective green to the cycle length ratio (g/c).

Although signal coordination has been studied from various perspectives including traffic...
volume, platoon dispersion, and signal spacing, none of them explicitly define when signals should be coordinated. As a consequence, in most cases, applying experience and engineering judgment deems necessary. Besides, previous studies and guidelines lack the consideration of the number of stops as a criterion in coordinating signals. Needless to say, reducing the number of stops is one of the operational objectives in designing signal-timing plans (12). Therefore, this paper addresses when signals should go into coordination by considering the number of stops that a vehicle will make while traveling along an arterial during actuated controlled operation of signals. The output of the proposed model is the level of traffic volumes in which signals should be coordinated with respect to two constraints: the desired number of stops and the probability of desired number of stops. The paper also conducted a survey on when U.S. traffic agencies turn on coordination plans in terms of traffic volume.

THE PROPOSED STOP BASED PROBABILITY MODEL

If signals are operating free (in actuated mode) and traffic volume is not very high, the arrival pattern of vehicles is assumed to be random. Thus, the probability that a vehicle hits the green at an intersection is the ratio of the effective green time to the actuated cycle length:

$$ p_i^g = \frac{g_i}{c_i} \quad (1) $$

Where,

- $p_i^g =$ probability of hitting green at intersection $i$,
- $g_i =$ actuated effective green time at intersection $i$,
- $c_i =$ actuated cycle length at intersection $i$,

Subsequently, the probability that a vehicle hits red would be the ratio of red interval ($r_i$) to the actuated cycle length:

$$ p_i^r = \frac{r_i}{c_i} = 1 - \frac{g_i}{c_i} = 1 - p_i^g \quad (2) $$

As proven in the authors’ previous work (11), when a vehicle travels along an arterial with $n$ intersections, the probability that the vehicle makes $x$ stops, $x \leq n$, can be calculated as follows:

$$ Pr(x) = \sum_{Z} \left\{ \prod_{i=1}^{n} p_i^g \cdot \prod_{j=1, j \neq i}^{n} (1 - p_j^g) \right\} \quad (3) $$

Where,

- $Pr(x) =$ probability of making $x$ stops,
- $n =$ total number of intersections,
- $i =$ intersection number at which the vehicle hits green,
- $j =$ intersection number at which the vehicles hits red,
- $Z =$ a set of possible combinations of $i$ and $j$ for $x$ stops out of $n$ intersections.

For example, considering an arterial with four intersection ($n = 4$), the probability that a vehicles makes two stops ($x = 2$), is determined by considering all possible combinations of making two stops as presented in Table 1.
Table 1 Possible Combinations of Making Two Stops out of Four Intersections; Z

<table>
<thead>
<tr>
<th>Event</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GO</td>
<td>GO</td>
<td>STOP</td>
<td>STOP</td>
</tr>
<tr>
<td>2</td>
<td>GO</td>
<td>STOP</td>
<td>GO</td>
<td>STOP</td>
</tr>
<tr>
<td>3</td>
<td>GO</td>
<td>STOP</td>
<td>STOP</td>
<td>GO</td>
</tr>
<tr>
<td>4</td>
<td>STOP</td>
<td>GO</td>
<td>GO</td>
<td>STOP</td>
</tr>
<tr>
<td>5</td>
<td>STOP</td>
<td>GO</td>
<td>STOP</td>
<td>GO</td>
</tr>
<tr>
<td>6</td>
<td>STOP</td>
<td>STOP</td>
<td>GO</td>
<td>GO</td>
</tr>
</tbody>
</table>

A good approximation to Equation (3) is the binomial distribution using the average of $\bar{p}_g$ as follows:

$$ Pr(x) = \binom{n}{x} (1 - \bar{p}_g)^x \cdot (\bar{p}_g)^{n-x} \quad (4) $$

$$ \bar{p}_g = \frac{\sum p_i^g}{n} \quad (5) $$

The probability that a vehicle makes less than a particular number of stops e.g., $X$ stops, while traveling along an arterial when signals are operating free can be determined as follows:

$$ Pr(x \leq X) = \sum_{x=0}^{X} \binom{n}{x} (1 - \bar{p}_g)^x \cdot (\bar{p}_g)^{n-x} \quad (6) $$

Consequently, the probability of making more than $X$ stops would be:

$$ Pr(x > X) = 1 - \sum_{x=0}^{X} \binom{n}{x} (1 - \bar{p}_g)^x \cdot (\bar{p}_g)^{n-x} \quad (7) $$

The probability of making more than $X$ stops along an arterial with 4, 6, and 8 intersections are calculated based on equation (7) for different effective green to cycle ($g/c$) ratios as depicted in Figure 1. In this figure, the desired number of stops is set to $0.5n$ which implies that the vehicles make stops at more than 50 percent of the intersections.

![FIGURE 1 Probability of Making More than 0.5n Stops (50 percent stops)](image-url)
In this part, the impact of $g/c$ ratio on the probability of stops is studied. However, in the process of decision making regarding the signal coordination, traffic engineers are used to dealing with the traffic volume rather than the $g/c$ ratio. Therefore, to make the stop based probability model more applicable, the authors make an attempt to find the relationship between the traffic volume and the $g/c$ ratio.

**Traffic Volume versus Actuated $g/c$ Ratio**

Lack of mathematical equations relating the traffic volume to the actuated $g/c$ ratio motivates the authors to find the relationship between these two parameters. In this regard, an actuated four-leg intersection with one shared lane for the through and right-turn movements and one left-turn pocket on each approach is modeled in Synchro.

The east-west approach is treated as the major approach and north-south as the minor approach. Several demand scenarios are generated with respect to the distribution of traffic between major and minor streets and also the directionality distribution of traffic on major and minor streets. Table 2 and 3 present the above mentioned scenarios.

### Table 2 Distribution of Traffic Volume between Major and Minor Streets

<table>
<thead>
<tr>
<th>Street</th>
<th>Scenario Number-SC#</th>
<th>01</th>
<th>02</th>
<th>03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td></td>
<td>0.55</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>Minor</td>
<td></td>
<td>0.45</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Table 3 Directionality Distribution on Major and Minor Streets

<table>
<thead>
<tr>
<th>Street</th>
<th>Approach</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td>EB</td>
<td>A 0.60</td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>A 0.40</td>
</tr>
<tr>
<td>Minor</td>
<td>NB</td>
<td>A 0.55</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>A 0.45</td>
</tr>
</tbody>
</table>

Another important input is the signal timing information including minimum green, maximum green, and vehicle extension, which are defined in Table 4.

### Table 4 Basic Signal Timing Information for Actuated Controlled Signals

<table>
<thead>
<tr>
<th>Street</th>
<th>Movement</th>
<th>Min Green (sec)</th>
<th>Max Green (sec)</th>
<th>Vehicle Extension (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td>Through</td>
<td>15</td>
<td>60</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Left-turn</td>
<td>5</td>
<td>15</td>
<td>3.0</td>
</tr>
<tr>
<td>Minor</td>
<td>Through</td>
<td>10</td>
<td>30</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Left-turn</td>
<td>5</td>
<td>15</td>
<td>3.0</td>
</tr>
</tbody>
</table>

The total traffic volume entering the intersection varies from 100 vph to 3000 vph.

Using the characteristics presented in Tables 2 through 4, the total six scenarios are defined and modeled in Synchro and the pertinent $g/c$ ratio is obtained using the HCM report.
The relationship between the traffic volume and the actuated \( g/c \) ratio with respect to the defined scenarios is depicted in Figure 2. In this figure, the demand scenarios are depicted as “\( SC_{i,j} \)” in which the parameter \( i \) represents the distribution of traffic volume between major and minor streets and it takes the values of 01, 02, and 03 associated with Table 2. The parameter \( j \) represents the directionality distribution of traffic and it takes the parameters A and B associated with Table 3. For instance, the demand scenario “\( SC_{01-B} \)” means the distribution of total traffic between major and minor streets is 0.55 to 0.45, respectively and the directionality distribution of traffic on the major street is 0.70 to 0.30 and 0.60 to 0.40 on the minor street.

FIGURE 2 Traffic Volume vs. Actuated \( g/c \) Ratio
Studying Figure 2 reveals that the relationship between the traffic volume and the actuated g/c ratio is quadratic. In addition, this figure shows that the distribution of traffic volume significantly impact the actuated g/c ratio.

**STOP BASED_THRESHOLDS**

The main application of the stop based probability model is to determine if signals should be coordinated or actuated. The operational signal timing plans can be determined by solving the following equation:

\[
\begin{align*}
\text{if} & \quad Pr(x \geq X) \geq K & \text{Run Coordination} \\
& \quad Pr(x \geq X) < K & \text{Run Actuated Control}
\end{align*}
\]

Equation (8) describes when the probability of making more than X stops exceeds K, a threshold value, signals should go into coordination. Otherwise, signals should operate as actuated controlled signals. In another word, when K portion of drivers make more than X stops, it deems necessary to turn on the coordination plans.

Solving the above equation requires establishing two thresholds: (1) the desired number of stops, and (2) the probability of desired number of stops. In this research, the following thresholds are established and studied:

- X = 0.4n and 0.6n
- K = 50, 60, 70, 80 percent

With respect to the established thresholds, first Equation (8) is solved and then Figure 2 is used to derive the associated traffic volume with the obtained g/c ratios. For all the demand scenarios, the traffic volumes associated with the defined thresholds are summarized in Table 5 and 6. At these levels of traffic volumes, the signals should go into the coordination.

### Table 5 Traffic Volumes Associated with the 40 Percent of Stops (X = 0.4n)

<table>
<thead>
<tr>
<th>Demand Scenario</th>
<th>SC_01_A</th>
<th>SC_02_A</th>
<th>SC_03_A</th>
<th>SC_01_B</th>
<th>SC_02_B</th>
<th>SC_03_B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>K</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>145</td>
<td>180</td>
<td>230</td>
<td>175</td>
<td>220</td>
<td>260</td>
</tr>
<tr>
<td>0.6</td>
<td>210</td>
<td>265</td>
<td>355</td>
<td>245</td>
<td>330</td>
<td>400</td>
</tr>
<tr>
<td>0.7</td>
<td>290</td>
<td>370</td>
<td>540</td>
<td>340</td>
<td>485</td>
<td>690</td>
</tr>
<tr>
<td>0.8</td>
<td>415</td>
<td>NA</td>
<td>NA</td>
<td>535</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

NA: Not Achievable

### Table 6 Traffic Volumes Associated with the 60 Percent of Stops (X = 0.6n)

<table>
<thead>
<tr>
<th>Demand Scenario</th>
<th>SC_01_A</th>
<th>SC_02_A</th>
<th>SC_03_A</th>
<th>SC_01_B</th>
<th>SC_02_B</th>
<th>SC_03_B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>K</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>315</td>
<td>410</td>
<td>600</td>
<td>375</td>
<td>525</td>
<td>715</td>
</tr>
<tr>
<td>0.6</td>
<td>405</td>
<td>565</td>
<td>685</td>
<td>510</td>
<td>690</td>
<td>865</td>
</tr>
<tr>
<td>0.7</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>0.8</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

NA: Not Achievable
Both tables clearly show that a lower threshold for the desired number of stops results in the lower level of traffic volume to trigger signal coordination plans. The interesting point in these tables is that at some levels of traffic volume, the probability of making a certain number of stops is not achievable. For instance, there is no condition that the probability of making more than 0.6\(n\) stops exceeds 0.7.

**CASE STUDY**

**Study Location**

Pyramid Way is one of the major arterials in the City of Sparks, Nevada that connect southern part of Sparks to the northern part. The arterial has two lanes on each direction with a left-turn lane pocket for left-turning vehicles. The arterial serves 20,000 vehicles per day in which the average directionality distribution between northbound (NB) and Southbound (SB) is 0.60 to 0.40. The average distribution between Pyramid Way and side street crossings is 0.65 to 0.35. Figure 3 shows the hourly traffic volume for the northbound and southbound directions which are considered as the major directions.

![FIGURE 3 24-Hour Traffic Volume Profile of Pyramid Way in Sparks, Nevada](image)

**Analysis and Results**

In order to apply the proposed stop probability model to determine the volume level for considering signal coordination, first it is necessary to identify the busiest direction along Pyramid Way as follows:

\[
MAX (NB & SB) = \max\{Vol^{NB}, Vol^{SB}\} \tag{9}
\]

Where,

\[
MAX (NB & SB) = \text{maximum hourly flow rate of NB and SB directions, vphpl},
\]

\[
Vol^{NB} = \text{hourly traffic volume of NB direction, vphpl},
\]

\[
Vol^{SB} = \text{hourly traffic volume of SB direction, vphpl}.
\]

The following thresholds are considered for the analysis purposes:

- \(Pr(x \geq 0.4n) \geq 0.7\)
- $Pr(x \geq 0.6n) \geq 0.5$

The first threshold gives the traffic volume in which more than 70 percent of drivers make more than 40 percent stops out of $n$ interactions. The second threshold gives the traffic volume in which more than 50 percent of drivers make more than 60 percent stops out of $n$ intersections. The maximum hourly volume and the threshold lines are depicted in Figure 4. It can be seen in Figure 4 that the associated traffic volume with the first threshold is 430 vphpl while with the second threshold is 470 vphpl. When the maximum traffic volume is above the threshold line, a coordination plan should be implemented and when it falls below the threshold line, the actuated controlled signals should be used.

![Figure 4: The Maximum Hourly Traffic Volume of Pyramid Way in Sparks, Nevada](image)

**TABLE 7** Recommended Time Periods to Run Coordination Plan along Pyramid Way in Sparks, Nevada

<table>
<thead>
<tr>
<th>Threshold</th>
<th>Time of Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Pr(x \geq 0.4n) \geq 0.7$</td>
<td>6:00-8:00</td>
</tr>
<tr>
<td>$Pr(x \geq 0.6n) \geq 0.5$</td>
<td>6:30-7:30</td>
</tr>
</tbody>
</table>

**THE ITE SURVEY ON SIGNAL COORDINATION**

A survey was conducted on the ITE website’s community section, inquiring at what level of traffic volume U.S. agencies implement signal coordination plans. It was found that the traffic agencies apply various traffic volumes ranging from 250 to 500 vphpl. For instance, the minimum threshold to trigger signal coordination by agencies in Florida, San Diego, Portland, and Sacramento is 280, 300/500, 300, and 360 vphpl, respectively.
Considering the stop probability analysis, it is realized that these agencies tend to set a low threshold for the desired number of stops, near 40 percent stops ($x \geq 0.4n$).

### SUMMARY AND CONCLUSIONS

The number of stops is one of the significant criteria in evaluating the performance of arterials, which has not received attention in the literature of signal coordination. This paper attempted to develop a method to determine when signal coordination plans should be on and off by considering the probability of stops. A probabilistic model was developed to predict the probability of making more than a certain number of stops along an arterial. The proposed model is a function of the number of intersections and the actuated effective green to cycle length ratio.

Since traffic engineers are used to dealing with the traffic volume to determine when signals should be coordinated, the authors were motivated to study the relationship between the $g/c$ ratio and the traffic volume. It turned out that there is a quadratic relationship between these two parameters. In addition, it was realized that directionality distribution of traffic significantly impacts the $g/c$ ratio.

In order to determine the timing periods for the signal coordination plans through the stop based probability model, two thresholds need to be set up: the desired number of stops and the probability of desired number of stops. The results showed that the lower the number of stops, the lower the level of traffic volume would be for signal coordination. A real case study in Sparks, Nevada was examined considering low and relatively high thresholds for a desired number of stops and subsequently, the timing periods to run the coordination plans were recommended based on these thresholds. It was also found that a higher threshold leads to running a coordination plan for a shorter period of time.

Finally, a survey was conducted regarding what level of traffic volume is used by some U.S. agencies to trigger signal coordination plans. The results of this survey revealed that these agencies tend to consider a low threshold for the desired number of stops.
REFERENCES


