A Method for Signal Coordination Decisions Based on Side-Street Traffic Volume

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Content

- Background
- Problem Description
- Simulation and Model Development
- Method for Signal Coordination Decisions
- Conclusions
Background

- Benefits of signal coordination
  - Reduced travel time
  - Reduced emissions
  - Improved safety
Background

Standards for signal coordination

- Intersection distance
  - Non-uniform guidelines
  - MUTCD: within 0.5 miles & same cycle
  - STM: “in close proximity” & “a large amount of traffic”
Standards for signal coordination

- Other simple criteria

Platoon dispersion not incorporated

1) Reduction in queue

\[ K = \frac{Q}{200(1 + t)} \]

Where:
- \( K \) = reduction in the queue (number of vehicles)
- \( Q \) = travel volume (number of vehicles/hr)
- \( T \) = travel time between intersections (minutes)
Background

- **Standards for signal coordination**
  - Other simple criteria
    - Platoon dispersion not incorporated
      - 2) "The Traffic Signal Book" method

\[ I = \frac{V}{L}, \quad I > 0.5 \]

Where:
- \( V \) = two way peak hour link volume (vph)
- \( L \) = Link length (feet)
Standards for signal coordination

- Other simple criteria
  - Platoon dispersion not incorporated

- 3) Coupling Index

\[ \text{CI} = \frac{V}{D^2} \]

Where:
\[ \text{CI} = \text{Coupling Index} \]
\[ V = \text{Two-way total traffic volume peak hour (1000 vph)} \]
\[ D = \text{Distance between signals (miles)} \]
Background

Summary

• Studied provided evidence for signal coordination needs during peak hours.

• Further study is necessary off-peak hours.

• Perception-based approaches
  • Delay (simulation software)
  • Number of stops

(# of stops would have more influence on driver perception of traffic efficiency during off-peak hours.)
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To find the impact of side-street volume on the green time, the intersection scenario is described as follows.

- four-leg intersection
- semi-actuated operation
- no fixed cycle length
- relatively low traffic volume
- minimum green time must be met
- right-of-way (green signal) remains 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.
Assumptions and pre-defined factors:

- Side street traffic is random, and combined.
- Major-street LT permitted.
- Side street signal can be extended.
- Side-street does not max out. (volume not sufficiently high)

Objective: Find the relationship between green ratio \((g/C)\) and side-street volume.
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Model Development

- **Simulation Model**
  - Generated a random vehicle arrival;
  - Simulated the corresponding signal operation process for a period of one hour under various volume scenarios;
  - Each volume scenario ran 100 times.
Model Development

Figure 1(a) Major-Street Green Ratio v.s. Side-Street Volume Simulation Model Results
Figure 1(b) Major-Street Green Ratio v.s. Side-Street Volume Simulation Model Results
Model Development

- A Probabilistic Model
  - Developed based on the simulation
  - Cycle = major-street green + side-street green + change/clearance intervals in between.

\[ C_{\text{mean}} = G_{\text{mean-major}} + G_{\text{mean-minor}} + T_{\text{intergreen}} \]
Model Development

- Parameters

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

- **Side-Street Vehicle Time Headway Distribution**

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

where $\Delta (\Delta \geq 0)$ is the minimum safety headway.

When $\Delta$ equals zero, Cowan’s M2 reduces to an exponential distribution.
Green Time Consumed by Major-Street

\[
G_{\text{mean\_major}} = \left( g_{\text{major\_min}} + \frac{3600}{q_{\text{minor}}} \right) \cdot (1 - \Pr(t_{\text{minor}} \leq g_{\text{major\_min}})) + g_{\text{major\_min}} \cdot \Pr(t_{\text{minor}} \leq g_{\text{major\_min}})
\]

\[
= \left( g_{\text{major\_min}} + \frac{3600}{q_{\text{minor}}} \right) - \frac{3600}{q_{\text{minor}}} \cdot \Pr(t_{\text{minor}} \leq g_{\text{major\_min}})
\]

\[
= g_{\text{major\_min}} + \frac{3600}{q_{\text{minor}}} \cdot (1 - \Pr(t_{\text{minor}} \leq g_{\text{major\_min}}))
\]

with the probability of gap on side-street being less or equal to \( g_{\text{major\_min}} \)

\[
\Pr(t_{\text{minor}} \leq g_{\text{major\_min}}) = 1 - (1 - \frac{q_{\text{minor}}}{3600}) \cdot \exp\left(-\frac{q_{\text{minor}}}{3600} \cdot (g_{\text{major\_min}} - \Delta)\right)
\]
- **Green Time Consumed by Side-Street**

  \[ G_{\text{mean\_minor}} = g_{\text{minor\_min}} + G_{\text{ext}} \]

  where \( G_{\text{ext}} \) is the mean green extension time.

  Mean green time extension on the side street is calculated as

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

- **Clearance Time Consumed between Green Intervals**

  \[ T_{\text{intergreen}} = y_{\text{major}} + a_r_{\text{major}} + y_{\text{minor}} + a_r_{\text{minor}} \]
Model Development

- A Probabilistic Model
  - major-street green time ratio =
    mean green on major street / mean cycle length

\[
R_{\text{major}} = \frac{G_{\text{mean\_major}}}{C_{\text{mean}}} = \frac{G_{\text{mean\_major}}}{G_{\text{mean\_major}} + G_{\text{mean\_minor}} + T_{\text{intergreen}}}
\]
Model Development

**Upper Limit of Side-Street Volume**

- Low volume condition
- Not consider side-street queue discharge
- Average queue discharge time $\geq$ side-street minimum green time

Model no longer fits
Model Development

- **Upper Limit of Side-Street Volume**
  - An estimation of average queue (measured in vehicles)

  \[
  \text{Queue}_{\text{avg}} = \frac{q_{\text{minor}}}{3600} (g_{\text{major_min}} + T_{\text{intergreen}})
  \]

  - The queue discharge time is

  \[
  T_{\text{dis}} = l_1 + \frac{\text{Queue}_{\text{avg}}}{s / 3600}
  \]

  where \( l_1 \) is start-up loss time and \( s \) is the saturation flow rate.
Model Development

- **Upper Limit of Side-Street Volume**

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

$$g_{\text{minor min}} = T_{\text{dis}}$$

$$g_{\text{minor min}} = l_1 + \frac{q_{\text{minor}}(g_{\text{major min}} + T_{\text{intergreen}})}{s / 3600}$$

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

- **HCM estimation: L1=2 sec, s= 1800vph**

$$q_{\text{minor}} = \frac{(g_{\text{minor min}} - l_1)s}{g_{\text{major min}} + T_{\text{intergreen}}} = \frac{1800(g_{\text{major min}} - 2)}{g_{\text{major min}} + 8}$$
The proposed model can appropriately estimate the major-street green time ratio under different side-street volume scenarios.
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Signal Coordination Decision

- If the major-street green ratios are in close proximity, the probability of a vehicle making \(x\) stops, when traveling along an \(n\)-intersection arterial, can be calculated by binomial distribution.

\[
Pr(X = x) = \binom{n}{x} \left( \bar{\rho}^g \right)^{n-x} \left( 1 - \bar{\rho}^g \right)^x
\]
Signal Coordination Decision

Steps:
- 1) Obtain g/C ratio for each intersection
- 2) get average g/C ratio
- 3) Set threshold for # of stops
- 4) Calculate the probability of making such number of stops or more
Signal Coordination Decision

Figure 2 Probability of Making 2 or More Stops

Pr(X ≥ 2) vs. Mean major-street green time ratio ($\bar{p}^g$)

- Blue line: n=4
- Red line: n=6
- Green line: n=8

Probability of Making 2 or More Stops

Pr(X ≥ 2) vs. Mean major-street green time ratio ($\bar{p}^g$)
Case Study

- Fourth Street in Reno, NV
- 4 intersections

Figure 3 Case Study Location
Case Study

- Hourly side-street volume and signal timing were obtained for 2 intersections.

![Figure 4 Side-Street Traffic Volume Profiles](image-url)
Case Study

Recommended time periods for coordination:

- \( \Pr(X \geq 1) > 0.9 \)
  - 6:45-19:30

- \( \Pr(X \geq 2) > 0.7 \)
  - 8:45-17:45

- Figure 5 Hourly Mean Major-Street Green Ratio
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Conclusions

• A probabilistic and simulation model was developed to evaluate the relationship between major-street green ratio and side-street traffic volume under low-volume scenarios.

• The probability of a major-street vehicle making a certain number of stops or more can be predicted.
Case study was conducted for a minor-arterial segment with four signals, located in Reno, Nevada. It was found that a lower tolerance of number of stops would lead to a longer period of signal coordination.

The decision-making method may be adopted by traffic engineers for the effective management of traffic signal networks.
Conclusions

- **Restrictions** 🤫
  - LT phases not considered
  - Did not consider side-street queue discharge
  - Did not consider major street extension

- **Further study**
  - To address the issues above
  - Compare results with commercial software
Acknowledgement

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Thank You!
Anyone interested in continuing the research?

"Hit Any Key To Continue"