Max-Pressure Traffic Signal Control Based On Bluetooth Sensor Data

Wasim Uwayid
Advisor: Jack Haddad

Technion Sustainable Mobility and Robust Transportation (T-SMART) Lab
Faculty of Civil and Environmental Engineering

Technion - Israel Institute of Technology

webpage: tsmart.net.technion.ac.il
email: w.uwayid@campus.technion.ac.il

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Introduction

Congestion in urban areas

- Increased congestion
- High demand
  - Long queues ⇒ spillback
  - Wasted green
  - Delay times
  - Under-utilized infrastructure
Introduction

Traffic control strategies

- **Pretimed strategies**
  - Fixed-time signal control
  - Historical data

- **Dynamic strategies**
  - Actuated/Adaptive
  - Real-time data
Classification of control strategies

- The classification described below concerns isolated signalized intersections.

### Fixed-time signal control

- Control variables, i.e. green durations, cycle length, and phases, are fixed
- Optimal control inputs are calculated offline
- Determined based on a priori known demand data
- Predefined optimized set of parameters
  - ← Saturation flows
  - ← Turn ratios
Classification of control strategies

- The classification described below concerns isolated signalized intersections.

### Fixed-time signal control
- Vehicle actuation changes the phases durations (and cycle length)
- Phase skip, gap acceptance, phase recall
- Predefined optimized set of parameters
  - Saturation flows
  - Turn ratios
- Offline calculations
- Operates in real time based on loop detector state
  - No systematic optimization

### Actuated signal control
- Applies an optimization algorithm in real-time to determine optimal signal timings
- Predefined or variable set of parameters
- Calculations based on measured initial traffic conditions (upstream information) and demand predictions
- Evaluation of a set of feasible actions; changing green time splits, cycle duration, phases' order
- An optimization problem is applied for a rolling horizon period
- High complexity
Classification of control strategies

- The classification described below concerns isolated signalized intersections.

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**Actuated signal control**
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- Phase skip, gap acceptance, phase recall
- Predefined optimized set of parameters
  - Saturation flows
  - Turn ratios
- Offline calculations
- Operates in real time based on loop detector state
  - No systematic optimization

**Adaptive signal control**
- Applies an optimization algorithm in real-time to determine optimal signal timings
- Predefined or variable set of parameters
  - Saturation flows
  - Turn ratios
- Calculations based on measured initial traffic conditions (upstream information) and demand predictions
- Evaluation of a set of feasible actions; changing green time splits, cycle duration, phases’ order
- An optimization problem is applied for a rolling horizon period
- High complexity
Centralized vs Decentralized

Large-scale networks

- **Looking on large-scale optimal performance (throughput, delay)**

- **Centralized structure**
  - global control actions
  - requires communication between controller and central computer
  - requires coordination between signalized intersections
  - most strategies require high computational complexity

- **Decentralized structure**
  - local control actions
  - requires low computational complexity
Control types of signalized intersections

- Centralized Controllers
  - Fixed time controller
  - Adaptive controller
    - Actuated signal controller
- Decentralized controllers
  - Max Pressure controller
    - Self-organized controller
Decentralized traffic controllers

Self-organized controller (LaemmerHelbing2008)

- *Based on heuristic on-line optimization*
- *Self-organized prioritization approach*  
  - Optimizing strategy ⇒ *minimizing the total waiting time*  
  - Stabilizing strategy ⇒ *maintain stability of queues*
- *Lack of a control plan*  
  - One approach has r.o.w for a predefined green time
- *Considers upstream queue lengths*
Decentralized traffic controllers

Self-organized controller ([LaemmerHelbing2008])

Max pressure controller

- Based on the difference between upstream and downstream queues
- No optimization method is applied
- Real-time calculations
- Lack of a control plan
  - one phase get r.o.w for a predefined green time period
  - same phase may have several consecutive predefined green time periods
Why Max-Pressure?

Downstream effect

- **Self-organized controller**
  - considers only upstream queues
  - may cause spillback to adjacent intersections
  - may cause in wasted green

- **Max-Pressure controller**
  - considers upstream and downstream queues
  - gives r.o.w to the "correct" approach
Max-Pressure algorithm

Max-Pressure concept (Varaiya2013)

- Max-Pressure was originally developed in wireless networks
- It was introduced to traffic signalized road networks modeled as network of queues
- The main idea of the algorithm is to consider the downstream link pressure
- Maximizing throughput
- Stabilizing the queues
- Algorithm inputs; queues, turn ratios, phases
Max-Pressure algorithm

Problem formulation

**Given:**
- queue lengths of the considered links
- phases
- turn ratios, saturation flows

**Determine:**
- the phase to be given r.o.w for a predefined green time period
Max-Pressure algorithm

**Problem formulation**

**Given:**
- queue lengths of the considered links
- phases
- turn ratios, saturation flows

**Determine:**
- the phase to be given r.o.w for a predefined green time period

**Notation**

- $Q_{i,m}(t) \text{[veh]} \Rightarrow$ queue length of link \( m \), of intersection \( i \)
- $Q_{j,c}(t) \text{[veh]} \Rightarrow$ queue length of link \( c \), of intersection \( j \)
- $\beta_{cm} \Rightarrow$ turn movement ratio from link \( c \) to link \( m \)
- $\beta_{mb} \Rightarrow$ turn movement ratio from link \( m \) to link \( b \)
- $s_{i,mb} \text{[veh/sec]} \Rightarrow$ saturation flow from link \( m \) to link \( b \), of intersection \( i \)
Steps of the algorithm

**STEP 1:** calculate the queue lengths

The queue length $Q_{i,m}(t+1)$ [veh] is calculated as follows

$$Q_{i,m}(t+1) = Q_{i,m}(t) + \sum_{c} \beta_{cm} \cdot Q_{j,c}(t) - \sum_{b} \beta_{mb} \cdot Q_{i,m}(t)$$
Steps of the algorithm

**STEP 1:** calculate the queue lengths

**STEP 2:** calculate the weights

The weight $w_{i,mb}(t)[\text{veh}]$ is defined as the difference between the upstream queue length $Q_{i,m}(t)[\text{veh}]$ and the downstream queue length $Q_{i,b}(t)[\text{veh}]$ at intersection $i$

$$w_{i,mb}(t) = Q_{i,m}(t) - Q_{i,b}(t)$$
Steps of the algorithm

**STEP 1:** calculate the queue lengths

**STEP 2:** calculate the weights

**STEP 3:** calculate the pressure

The pressure \( p_{i,mb}[\text{veh}^2/\text{sec}] \) is defined as the weight \( w_{i,mb}(t)[\text{veh}] \) multiplied by the saturation flow \( s_{i,mb}[\text{veh/sec}] \)

\[
p_{i,mb}(t) = w_{i,mb}(t) \cdot s_{i,mb}
\]
Steps of the algorithm

**STEP 1:** calculate the queue lengths

**STEP 2:** calculate the weights

**STEP 3:** calculate the pressure

**STEP 4:** apply green time

The MP policy applies a green time step previously defined to the phase with the highest pressure.
Variations of Max-Pressure algorithm

Different MP algorithms in the literature

- Determining green time splits ([Kouvelas, 2014](#))
- Using normalized weights ([Gregoire, Qian, Frazzoli, et al., 2015](#))
- Using exponential weights ([Gregoire, Qian, Frazzoli, et al., 2015](#))
- Virtual queues ([Zaidi, Kulcsar, Wymeersch, 2015](#))
- Adaptive routing ([Zaidi, Kulcsar, Wymeersch, 2015](#))

All previous MP algorithm controllers are queue-based feedbacks.
Variations of Max-Pressure algorithm

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Variations of Max-Pressure algorithm

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Loop detectors vs BT sensors

<table>
<thead>
<tr>
<th></th>
<th>Loop detectors</th>
<th>BT sensors</th>
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</thead>
<tbody>
<tr>
<td><strong>estimated variables</strong></td>
<td>occupancy, flow, queues</td>
<td>travel time, turn ratios, route-choice</td>
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<tr>
<td><strong>Data collected</strong></td>
<td>all</td>
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<tr>
<td><strong>Cost</strong></td>
<td>expensive</td>
<td>cheap</td>
</tr>
<tr>
<td><strong>Installation</strong></td>
<td>complex</td>
<td>facilitate</td>
</tr>
</tbody>
</table>
Motivation

- Queue-based feedback $\Rightarrow$ Travel-time based feedback
- Travel time is another index for estimating delay time
- New MP algorithm based on travel time information
- Bluetooth sensors estimate average travel time
Developed Max-Pressure algorithm

Problem formulation

**Given:**
- average travel times of all links considered
- control plan; cycle time, phases and its order, lost time

**Determine:**
- green time durations for all phases
Developed Max-Pressure algorithm

Problem formulation

Given:
- average travel times of all links considered
- control plan; cycle time, phases and its order, lost time

Determine:
- green time durations for all phases

Notation

- $g_{min}$ [sec] ⇒ minimum green time allocated for each phase of control plan’s phases
- CYC [sec] ⇒ the cycle time of the control plan
- $L$ [sec] ⇒ the total lost time occurs when switching between the phases
- $V$ [-] ⇒ the set of all phases
- $s_{lk}$ [veh/sec] ⇒ the saturation flow of the turn movement from link $l$ to link $k$
Steps of the algorithm

- Green time split is determined according to a priori given fixed cycle time \((\text{kouvelas2014maximum})^a\)
- Effective green time \(G \Rightarrow\) the total green time available for splitting over the phases

\[
G = CYC - L - \sum_{a \in V} g_{\text{min}}
\]

- Where:
  \(\leftarrow V[-] \Rightarrow\) set of all phases

\(^a\text{kouvelas2014maximum.}\)
Steps of the algorithm

**STEP 1: calculate the average speed**

Let $VEL_{j,l}(t) \ [\text{m/sec}]$ be the average speed of link $l$, which belongs to intersection $j$. The average speed is calculated as follows

$$VEL_{j,l}(t) = \frac{L_{j,l}}{TT_{j,l}(t)} \quad \forall l \in j$$

where:

- $\rightarrow L_{j,l} [\text{m}] \Rightarrow$ the length of link $l$
- $\rightarrow TT_{j,l}(t) [\text{sec}] \Rightarrow$ the average travel time in link $l$
Steps of the algorithm

**STEP 1:** calculate the average speed

**STEP 2:** calculate the weights

The weight $w_{j,lk}[m/s]$ is defined as the difference between the average speed of the downstream link $k$, which belongs to intersection $i$, and the upstream link $l$, which belongs to intersection $j$

$$w_{j,lk} = VEL_{i,k}(t) - VEL_{j,l}(t)$$

where:

- $VEL_{i,k}(t)[m/sec]$ ⇒ the average speed of link $k$, which belongs to intersection $i$
- $VEL_{j,l}(t)[m/sec]$ ⇒ the average speed of link $l$, which belongs to intersection $j$
Steps of the algorithm

**STEP 1:** calculate the average speed

**STEP 2:** calculate the weights

**STEP 3:** calculate the pressure and the pressure ratios

The pressure term $p_a$ contains the sum of all weights belonging to phase $a$, previously defined, multiplied by the saturation flow $s$

$$p_a = \sum_{(l,k) \in v_a} (w_{lk} \cdot s_{lk}) \quad \forall a \in V$$

where:

$\Leftarrow v_a[-] \Rightarrow$ contains all $(l, k)$ pairs belonging to phase $a$

$\Longrightarrow$ The pressure ratio $P_a$ is calculated as follows

$$P_a = \frac{p_a}{\sum_{b \in V} p_b} \quad \forall a \in V$$
Steps of the algorithm

**STEP 1:** calculate the average speed

**STEP 2:** calculate the weights

**STEP 3:** calculate the pressure and the pressure ratios

**STEP 4:** apply green duration

The green split is determined according to the pressure rates calculated. Each phase is allocated with green time portion from total green time available

\[ g_a = P_a G + g_{min} \quad \forall a \in V \]

where:

\( g_a [\text{sec}] \Rightarrow \) the green time allocated for phase \( a \)
Simulation environment

Simulations

- The micro-simulations consists of 1 hour simulation
- The results for each micro-simulation are an average of 10 replications
Simulation environment

Network types

- **Isolated**: an isolated intersection
- **Network**: five signalized intersections
Results for Isolated Intersection

Isolated intersection

- Three possible turn movements; left, right, through
- No disturbances available to emphasize the controllers’ pure effect
- Three control methods were examined; fixed-time control plan, MP based on queue lengths, MP based on travel time
- Demand was chosen arbitrary
Queue length comparison

(a) Symmetric demand
(b) Symmetric demand
(c) Different demand
(d) Different demand
Throughput comparison

uncongested

congested

Throughput comparison graphs showing the performance of different traffic signal control methods under uncongested and congested conditions.
Results of five intersections

Five intersections

- *Three possible turn movements; left, right, through*
- *Both MP algorithms are applied on all intersections*
- *Three control methods were examined; fixed-time control plan, MP based on queue lengths, MP based on travel time*
- *Demand was chosen arbitrary*
Queue length comparison

**uncongested**

![Graph of queue length comparison in uncongested](image)

**congested**

![Graph of queue length comparison in congested](image)

Symmetric demand

Different demand
Throughput comparison

(a) Symmetric demand
(b) Different demand

Max-Pressure Traffic Signal Control Based On Bluetooth Sensor Data
Case study

- Implementing and applying the developed MP algorithm to a real arterial
- An arterial in Jerusalem is chosen as the study site
- The arterial, Knafie NesharinHarav Tsvi Yehuda, consists of 3 intersections
- Another intersection linked with the arterial
- For investigating the current performance of the arterial, we have modeled the arterial with a micro-simulation based on real-data of the considered intersections
Case study
Case study
Case study

Deployment of sensors

- Deployment of CCTV cameras
- Deployment of Bluetooth sensors
- Deployment of magnetic loop detectors
Case study

**Deployment of sensors**

- Deployment of CCTV cameras
- Deployment of Bluetooth sensors
- Deployment of magnetic loop detectors
Case study

Case study network

- Four intersections
- Arterial with three intersections, another branched intersection
- One main intersection MP algorithms applied on
- Demand given by Jerusalem control center
- Three control methods were examined; fixed-time control plan, MP based on queue lengths, MP based on travel time
Queue length comparison

uncongested

congested

(a)

(b)

(c)

(d)
Throughput comparison

uncongested

congested

(a) (b)

(c) (d)
Case study

Bluetooth penetration rates

- Bluetooth sensors are used to estimate the travel time
- Penetration rates are the percentage of vehicles collected using bluetooth sensors from all existing vehicles
- A simulation is modeled using different penetration rates to depict the effect on the quality of the developed MP algorithm
Throughput comparison

(a) uncongested

(b) congested
Case study

Bluetooth data analysis

- The different links of the case study network are analyzed
- The analysis is regarding bluetooth penetration rates and its deviation for a period of one month
- Analysis of one link is presented. In terms of bluetooth sensors, a link is a section between two consecutive bluetooth sensors
- The figure below depict the available bluetooth sensors and its positions in the network
Case study

Bluetooth data analysis example

- The analyzed section is between the two bluetooth sensors $TS_1$ and $TS_2$
- The analysis is regarding bluetooth penetration rates and its deviation for a period of one month
- Depicted below, the hourly penetration rates of each hour for a period of one month and its deviation
Summary & Conclusions

Summary

- Presenting max-pressure algorithm as in literature
- Suggesting new input for the max-pressure algorithm and formulating its steps
- Conducting micro-simulation analysis over different networks including a real case study
- Results of the simulations in terms of queue lengths and throughput were presented
- Depicting the effect of bluetooth penetration rates on the quality of the developed algorithm and analysis of bluetooth real data

Conclusions

- The developed Max-Pressure controller based on travel time information can be utilized for traffic networks
- The developed Max-Pressure controller can perform efficiently if we ensure more than 10% penetration rate in average
Thank You!