A Priority System for Multi-Modal Traffic Signal Control

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Motivation

• Cars are not the only users at an intersection.

• Need a methodology to determine the “best way” to serve multiple intersection users.
Initially, intersection operation was basic........

For each of the safe combinations of movements – given the geometry.....

**Efficiency** was the primary objective

Green, Yellow, Red

Not too complicated!
Traffic Signal Controller Features – How did we get here???

- “Why should I wait when there are no opposing vehicles?”
- “I want to safely walk across the street”
- “I want to progress through all of the intersections on the arterial.”
- “What do we do about the train crossing the road?”
- “The Emergency Vehicles shouldn’t be delayed!”
- “Why do you stop my buses?”

**Vehicle Actuated Control**

**Pedestrian Intervals**

**Coordination**

**Railroad Preemption**

**EV Preemption**

**Transit Priority**
...so we “progressed” from efficiency first to multi-modal efficient/safety AND quality of service....
...and now into an **information rich environment** for...advanced decisions
New Controller Paradigm in an Connected Vehicle Environment…..

• “Warn me if a vehicle is going to violate a signal control”
• “Can the signal change to help prevent an accident?”
• “How is the signal performing?”
• “Can you optimize signal timing in real-time?”
• “What if several buses arrive at the same time?”
• “I can’t always see the traffic signal (e.g. behind truck in left turn lane)
Multi-modal Considerations for Connected Vehicles....

- “Warn me if a pedestrian is in my vehicle path”
- “Extend the pedestrian clearance interval to ensure pedestrians safely cross the street”
- “Shorten the phase time if there are no pedestrian”
- “Extend the green for a high speed truck”
- “Release the bicycles before the vehicles to avoid right turn conflicts”
- “Coordinate signal timing for Emergency Vehicles”

**Active Pedestrian Signal Control**

**Multi-modal Control and Priority**

**Emergency Vehicle Infrastructure Integration**
What are Connected Vehicles?

- Also known as Vehicle Infrastructure Integration (VII), Vehicle-to-Vehicle (V2V), and Vehicle-to-Infrastructure (V2I)
- On-board Equipment (OBE) with DSRC (Dedicated Short Range Communications) radios at 5.9 GHz, and GPS receivers
- Roadside equipment (RSE) with DSRC and signal controller
- MAP and SPaT describe geometry and operational state
- V2X (vehicle-to-vehicle and vehicle-to-infrastructure) wireless communication
- A “Backhaul” network will transport this roadside data to/from a central location.
US DOT/RITA
Connected Vehicle Program

• Focus Areas
  – Connected Vehicle Technology
  – Connected Vehicle Applications
  – Connected Vehicle Technology Policy and Institutional Issues
  – Use of Dedicated Short Range Communications

Source: http://www.its.dot.gov/connected_vehicle/connected_vehicle.htm
US DOT/RITA

Connected Vehicle Program

• Connected Vehicle Applications
  – Vehicle to Vehicle (V2V) Communications for Safety
  – Vehicle to Infrastructure (V2I) Communications for Safety
  – Real-Time Data Capture and Management
  – Dynamic Mobility Applications
  – Road Weather Management
  – Applications for the Environment: Real-Time Information Synthesis (AERIS)
An Intersection
An equipped intersection

- MAP GPS Waypoints
- OBE
- Signal Controller
- RSE
- Wifi? Bluetooth?
- 3G, 4G LTE
- DSRC 5.9GHz?
Traffic Signal Priority in an Connected Vehicle Environment

0. Broadcast(MAP) (every 1 second)

5. Priority(#1,#2)

4.2 evaluate(timing)

3. Request(time)

4.1 V2V(“Here I am”)

6. SignalStatus()

1. Request(time)

Assume Emergency Vehicles have OBE
The Need for Intelligent Traffic Signal Priority

Houston – March 30, 2009

• “The Houston Fire Department says both trucks were on the same call -- an apartment fire that ended up being a false alarm. While firefighters rush to every call, a fire department spokesman says Monday's accident was unexpected.”

St. Louis – October 10, 2008

http://firegeezer.com/2008/10/10/fire-truck-collision-in-st-louis/
Brooklyn October 23, 2009

“Two fire trucks racing to an emergency collided in Brooklyn Saturday - injuring a dozen firefighters, including one who was pinned for two hours and emerged to cheers.”

Read more: http://www.nydailynews.com/ny_local/2009/10/24/2009-10-24_several_firefighters_injured_after_two_fire_trucks_collide_in_.html#ixzz0c3cycoUx
Avondale, AZ – February 5, 2010

“A police car and an ambulance were involved in a collision on their way to another wreck in Avondale early Friday morning....

According to Avondale police, one of their cruisers was on its way to that wreck and had slowed down to start a traffic control when an ambulance heading to the same scene hit the police car....

The ambulance was not going too fast at the time, so the damage to the vehicles was minor and no injuries were reported.”


From:
Barbara Hauser – MCDOTX
Faisal Saleem – MCDOTX
National Emergency Responder Issues

• EMS vehicles respond to 30 million calls annually
• Crash Fatality Rate for EMS is 10 fold higher than heavy trucks
• Highway related incidents represent the second highest cause of police officer fatalities
• Nearly 13% of Fire and Rescue deaths & injuries are attributed to highway and traffic events

Source: TSAG Comments on ITS Strategic Plan (2010-2015) [February 8, 2010]
Traffic Control Terminology

Movements
Phases
Detectors

Dual Ring, 8-Phase Controller
A Core Logic Model

Dual Ring Controller (Core Logic)

Precedence Diagram

Cycle 1 Cycle 2

(work for general precedence relationships – not just dual ring)
Every phase is composed of **intervals** that control how phases are timed.
Phase Configuration and Real-time Data

**Structural Parameters**

<table>
<thead>
<tr>
<th>Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>X X X X X</td>
</tr>
<tr>
<td>X Omit, etc.</td>
</tr>
</tbody>
</table>

**Timing Values**

- Phase 1 2 3 4
- Min 12 15 10 10
- Max 45 45 30 30

**Priority requests**
- Vehicle/ped calls
- Preemption calls
- Advanced detection data

**Real-time Demand parameters**

**Precedence Network Model**
Requests for Priority

- Preemption
  - Heavy Rail
  - Emergency Vehicles*

Request for Phase 8 at t=38

Priority

- Buses
- Light Rail
- Snow Plows
- Trucks
Multiple Requests for Priority

There could be many requests from many vehicles
Priority Request Management

**Priority Request Generator**
- On-vehicle system that is responsible for knowing the vehicle position, velocity, route, and relation to intersection (via MAP or other)
- Vehicle must compute the desired service time from position, velocity (desired and actual), and relation to intersection
- Vehicle must request desired phase (information is in MAP or other) based on desired route
- Vehicle must cancel, or signal, when priority is no longer needed – either when served or when cancelled
- Vehicle must update request when arrival time changes

**Priority Request Manager**
- Responsible for gathering requests and updates from vehicles [Priority Request Generators], solving the priority timing problem, and making a schedule available to the Priority Timing Controller
- Responsible for limiting number of active requests to maxRequests
- Responsible for managing different classes of service (Fire, Ambulance, Police, etc.) and implementing a priority policy
Priority Request Manager

ActiveRequests (Table)

• This is a table of currently active priority requests that are being served by the Priority Timing Controller.

• A Priority Policy determines the service hierarchy and relative importance:
  – Dispatch Response Code (?)

Example Table

<table>
<thead>
<tr>
<th>PK-ID</th>
<th>Class</th>
<th>Time</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIN_1</td>
<td>1</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>VIN_2</td>
<td>1</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>VIN_3</td>
<td>2</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>VIN_4</td>
<td>3</td>
<td>23</td>
<td>6</td>
</tr>
</tbody>
</table>
Model Formulation

Minimize Total Priority Delay + Vehicle Cost

s.t.

Precedence Constraints

Phase Duration & Interval Constraints

Service Phase Selection Constraints

Phase Calls and Flags

Decision Variables:

phase start times = $t^j_p$, durations = $v^j_p$

green time = $g^k_p$, given yellow = $y^j_p$, red = $r^j_p$

$$v^k_p = \begin{cases} 
  g^k_p + y^j_p + r^j_p & \text{if } g^k_p > 0 \\
  0 & \text{if } g^k_p = 0 
\end{cases}$$

service phase = $\theta^i_e \theta^j_s \in \{0,1\}$, phase and interval skipping = $S_{-}^j_p \in \{0,1\}$
Precedence Constraints

\[ t_1^1 = 0 \]
\[ t_1^2 = 0 \]
\[ t_3^k = t_1^k + v_1^k \]
\[ t_6^k = t_5^k + v_5^k \]
\[ t_3^k = t_2^k + v_2^k, \quad t_3^k = t_6^k + v_6^k \]
\[ t_7^k = t_2^k + v_2^k, \quad t_7^k = t_6^k + v_6^k \]
\[ t_4^k = t_3^k + v_3^k \]
\[ t_8^k = t_7^k + v_7^k \]
\[ t_1^{k+1} = t_4^k + v_4^k, \quad t_1^k = t_8^k + v_8^k \]
\[ t_5^{k+1} = t_4^k + v_4^k, \quad t_5^k = t_8^k + v_8^k \]

for \( k = 1, K \), \( K \)

for \( k = 1, K \), \( K - 1 \)
Phase Duration Constraints

\[ t^k_p \geq 0, \]

\[ g^k_p (\Omega, \Phi, \omega, s^k_p) \leq g^k_p \leq g^k_p (\Omega, \Phi, \omega, s^k_p), \quad \text{for all } p \text{ and } k \]

where,

\( \Omega \) is a vector of phase parameters (min, max, walk, dfw, ext,...)
\( \Phi \) is a vector of phase flags (recall, omit, etc.), and
\( \omega \) is a vector of real-time phase calls (vehicle, ped), and
\( s^k_p \) are binary interval decision variables (skip, don't skip)
Phase Interval Constraints

\[ g_p = \text{Max} \left\{ D \min_p \cdot (1 - X \min R_p), \right. \]
\[ \left. D \min_p \cdot Cphs_p \cdot (1 - S \min_k^p), \right. \]
\[ \left. (Dw_p + Dfdw_p) \cdot Cped_p \cdot (1 - Sped_p^k), \right. \]
\[ \left. D \max_p \cdot X \max R_p \right\} \cdot (1 - SC_p^k) \cdot (1 - Xomit_p) \]

\[ g_p = \left\{ \max \left( D \max_p, (Dw_p + Dfdw_p) \cdot Cped_p \right) \right\} \cdot (1 - SC_p^k) \cdot (1 - Xomit_p) \]

Notation

- \( D \) = Phase Parameters (\( \Omega \))
- \( X \) = Phase Flags (\( \Phi \))
- \( C \) = Phase Calls (\( \omega \))
- \( S_{-p}^k \) = Phase Skip Decision Variable
Service Phase Selection Constraints

$\theta_{j,k}^{p,e,1} \in \{0,1\}$ serve Request $j$ before phase $(p)$ in the $k^{th}$ cycle

$\theta_{j,k}^{p,s,1} \in \{0,1\}$ serve Request $j$ during phase $(p)$ in the $k^{th}$ cycle

$\sum_{k} \theta_{p,e}^{j,k} + \theta_{p,s}^{j,k} = 1$

for every priority request $R_j^p$
Service Phase Selection Constraints

\[ t^1_p - R^j_p \geq (\theta_{p,e}^{j,1} - 1)M \]
\[ t^1_p + v^1_p - R^j_p \geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} - 1)M \]
\[ t^2_p - R^j_p \geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2} - 1)M \]
\[ t^2_p + v^2_p - R^j_p \geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2} - 1)M \]
\[ t^3_p - R^j_p \geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2} + \theta_{p,e}^{j,3} - 1)M \]
\[ t^3_p + v^3_p - R^j_p \geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,3} + \theta_{p,e}^{j,3} - 1)M \]

\[ R^j_p - t^1_p \geq -\theta_{p,e}^{j,1}M \]
\[ R^j_p - (t^1_p + v^1_p) \geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1})M \]
\[ R^j_p - t^2_p \geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2})M \]
\[ R^j_p - (t^2_p + v^2_p) \geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,2})M \]
\[ R^j_p - t^3_p \geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,3} + \theta_{p,e}^{j,3})M \]
\[ R^j_p - (t^3_p + v^3_p) \geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,3} + \theta_{p,e}^{j,3} + \theta_{p,s}^{j,3})M \]
Total Priority Delay

Minimize \[ D = \sum_{(p,j)} \sum_k \theta^{j,k}_{p,e} (t^k_p - R^j_p) \]
Some Issues/Enhancements

- Model is mixed integer-nonlinear
- Model doesn’t account for coordination behavior
- Model results in fixed time control, e.g. phases are not actuated based on vehicles calls (detection)
- Priority requests are points in time, in reality there is uncertainty in arrival times (Robust)
- Solution uses commercial solvers (CPLEX)

Qing He, PhD, July 2010
**Deterministic. MILP Formulation**  
(revised from Head et al. 2006)

Minimize: total priority delay \[ \sum_{j,p,k} D_{jpk} \]

Subject to

**Precedence constr.**

\[ E t^1 = 0 \]

**Serving cycle selection constr.**

\[ R_{jp} \leq t_{pk} \]

**Delay evaluation constr.**

\[ D_{jpk} \geq t_{pk} - R_{jp} - (1 - \theta_{jpk})M \quad \forall j, p, k \]

\[ D_{jpk} \geq 0 \quad \forall j, p, k \]

**Phase duration constr.**

\[ g_{pk}^{\min} \leq g_{pk} \leq g_{pk}^{\max} \quad \forall p, k \]

Data: \( R_{jp}, g_{pk}^{\min}, g_{pk}^{\max} \)

Variable: \( D_{jpk}, t_{pk}, g_{pk}, \theta_{jpk} \)

Delay for \( j \)th request with phase \( p \), served in cycle \( k \).

Arrival time for \( j \)th request with phase \( p \).

Dual-ring, eight-phase controller
Robust Multiple Priority Control

Phase-time diagram representation of a dual-ring controller
Robust Multiple Priority Control

Interval Requests

Interval request representations on phase-time diagram

Robust interval (a) Cyclic serving rectangles (CSR) for an interval priority request; (b) Four possible service cases for a CSR

1: Cannot serve any possible requests
2: Can serve a fraction of requests
3: Can serve all requests with NO delay
4: Can serve all requests with some delay
Plan implementation with realized actuations

Actuated control

Model green extension time for actuated control

\[ g_{pk} = g'_{pk} + a_{pk} \quad \forall p, k \]

- \( g_{pk} \): Necessary green time for phase \( p \) at cycle \( k \)
- \( g'_{pk} \): Maximal green extension time for phase \( p \) at cycle \( k \)
- \( a_{pk} \): Maximal green extension time for actuated control
Plan implementation with realized actuations

Green extension reassignment- Green extension group (GEG)

\[ \sum_j \theta_{jk} \]: Number of requests served in phase \( p \) cycle \( k \)

\( s_{GEG[i]} \): a set of phases in GEG \( i \)

\( t_{GEG[i]} \): total green extension time in GEG \( i \)

\[ t_{GEG[i]} = \sum_{(p,k)} a_{pk} \quad \forall (p,k) \in s_{GEG[i]} \]
Plan implementation with both priority and coordination requests
Signal coordination by virtual coordination requests

\[ R_{p,k}^c \in [\underline{R}_{p,k}^c, \overline{R}_{p,k}^c] \]

- Represent splits by \( \overline{R}_{p,k}^c - \underline{R}_{p,k}^c \)

- Represent offsets by \( R_{p,k}^c \)

- Represent common cycle length by \( R_{p,c,k+1}^c = R_{p,c,k}^c + C \quad \forall p_c, k \)
Multiple Priority Control with Signal Coordination

Signal optimization for both priority and coordination requests

Minimize

\[ \alpha \sum_{j,p,k} w_{jp} d'_{jpk} + \gamma \sum_{p_c,k} w_{p_c,k} d^c_{p_c,k} - \beta \sum_{p,k} a_{pk} \]

Subject to

1) Precedence constraints
2) Cycle selection constraints
3) Delay evaluation constraints

\( w_{jp} \): Weight for priority request \((j,p)\)
\( w_{p_c,k} \): Weight for coordination request \((j,p)\)
\( d'_{jpk} \): Priority delay in cycle \(k\) for priority request \((j,p)\)
\( d^c_{p_c,k} \): Coordination delay in cycle \(k\) for coordinated phase \(p_c\)
\( a_{pk} \): green extension time for actuated control at phase \(p\) during cycle \(k\)

\( \alpha, \beta, \gamma \): Weighting factors
Search for a near optimal cut combination by delay evaluation from phase-time diagram.

An example of delay evaluation:

- Request list for phase 2: \{1, 2\}.
- Request list for phase 4: \{1\}.
- Cut combination: \{c_1 = 0, c_2 = 2, c_3 = 0, c_4 = 2\}

\(c_p\): cut position for phase \(p\)
In this case, both algorithms get the same results, so does the GLPK/CPLEX.
Heuristic

Developed by Jun Ding, MS/PhD Student
The results obtained by GAMS/CPLEX method are slightly different from the previous results.
Implementation & Evaluation

• Simulation evaluation
  – VISSIM
  – Transit Priority (since VISSIM doesn’t model EV)

• ADOT E-Connected Vehicle Project
  – Field Demonstration
  – Live Intersection Implementation
Simulation Results

Evaluation platform and test intersections
Simulation Results

Performance comparisons with state-of-practice method “ASC-TSP coord”: Econolite Transit Signal Priority for ASC/3 with SYNCHRO optimized coordination
Network Extensions

- Why consider only one intersection?
- Assume that all vehicles are equipped and send requests for priority
Assumptions of PAMSCOD (Platoon-based Arterial Multi-modal Signal Control with Online Data)

1) Each vehicle is equipped with OBE. So 100% penetration is assumed.

2) Only two travel modes are considered: automobiles and buses.
Traffic control within a v2x environment – Hierarchical platoon recognition

Features of Hierarchical platoon recognition

1) Generate different headway level of platoon recognition.

2) Different headways can be applied on the same link, so it is able to output desired predefined number of platoons.
Traffic control within a v2x environment – Hierarchical platoon recognition

- An example of 2-level clustering with 2s and 1s headways respectively

\[ h[12] = 2s \]

\[ h[16] = 1s \]

\[ h[20] = 1s \]

\[ T_p = 3600N_p / S_r + T_{st} \]

\[ 0 \leq T_a < T_{\bar{a}} \]

\[ T_p = T_{\bar{a}} - T_a \]
Unified:
- Consider phase precedence through all intersections in the network.
- Consider different starting phase combinations through all the intersections.

Set control for different starting phase combinations at intersection $i$.

$$\Delta_{s1}(i) = \{4\}, \Delta_{s2}(i) = \{7\}, \Delta_{p}(i) = \{1, 2, 3, 5, 6\}, \Delta_{non}(i) = \{\}$$
Traffic control within a v2x environment –
Serving cycle selection constraints

Original constraints

\[ T_a(m, i, p, j) + T_p(m, i, p, j) \leq t(i, p, k) + g(i, p, k) + M(1 - \theta(m, i, p, j, k)) \quad \forall (m, i, p, j) \in \Gamma, k \]

\[ T_a(m, i, p, j) + T_p(m, i, p, j) \geq t(i, p, k) + g(i, p, k - 1) - M(1 - \theta(m, i, p, j, k)) \quad \forall (m, i, p, j) \in \Gamma, k \]

\[ \sum_k \theta(m, i, p, j, k) = 1 \quad \forall (m, i, p, j) \in \Gamma \]

Constraints with platoon splits

\[ T_a(m, i, p, j) + T_p(m, i, p, j) \leq t(i, p, k) + g(i, p, k) + M(1 - \theta(m, i, p, j)) \quad \forall (m, i, p, j) \in \Gamma, k \]

\[ T_a(m, i, p, j) + T_p(m, i, p, j) \geq t(i, p, k - 1) + g(i, p, k - 1) - M(1 - \theta(m, i, p, j)) \quad \forall (m, i, p, j) \in \Gamma, k \]

\[ \sum_k \theta(m, i, p, j, k) = 1 \quad \forall (m, i, p, j) \in \Gamma \]

\[ d_{pen}(m, i, p, j) = Np(m, i, p, j)(1 - c_i(m, i, p, j)) C_r \quad \forall (m, i, p, j) \in \Gamma \]
Traffic control within a v2x environment –
Delay evaluation: queue delay and signal delay

\[
\begin{align*}
&d_q(m,i,p,j)/N_p(m,i,p,j) \geq t(i,p,k) + \sum_{j \neq j} N_p(m,i,p,j) * L_s / N_i(i,p)/V_s \\
&- (T_o(m,i,p,j) - \sum_{j \neq j} N_p(m,i,p,j) * L_s / N_i(i,p)/V_p(m,i,p,j)) \\
&- M(1-\theta(m,i,p,l,k)) \quad \forall (m, i, p, j) \in \Gamma, k
\end{align*}
\]

\[
\begin{align*}
d_s(m,i,p,j) & \geq \sum_{n=1}^{N_p(m,i,p,j)} \{t(i,p,k) + \sum_{j_1=1}^{j-1} [\theta(m,i,p,j_1,k) * T_p(m,i,p,j)] \} \\
&(n-1)H_s(m,i,p,j) - [H_o(m,i,p,j) + (n-1)H_p(i,p)] \\
&- M(1-\theta(m,i,p,j,k), k) \quad \forall j \geq 2, (m, i, p, j) \in \Gamma, k
\end{align*}
\]
Traffic control within a v2x environment – Multi-modal dynamic progression

Features
1) Coordination with different travel modes
2) Dynamical coordination for real-time platoons
3) No common cycle length required
Assumption

1) First-come first-serve (FCFS) rule holds for the requests in the same phase and same mode

$$\theta(m, i, p, j, k) \leq \sum_{c=k}^{\mid K \mid} \theta(m, i, p, j + 1) \quad \forall (m, i, p, j) \in \Gamma$$

$$\theta'(m, i, p, j, k) \leq \sum_{c=k}^{\mid K \mid} \theta'(m, i, p, j + 1) \quad \forall (m, i, p, j) \in \Gamma_2 \cup \Gamma_6$$

$$\theta(m, i_d, p, j, k) \leq \sum_{c=k}^{\mid K \mid} \theta'(m, i, p, j, c) \quad \forall (m, i, p, j) \in \Gamma_2 \cup \Gamma_6, i_d \in I_d(i, p)$$
Traffic control within a v2x environment –
Objective of the Entire Formulation

Minimize \[ \sum_{(m,i,p,j) \in \Gamma} W(m,i,p,j) \right\| d_s(m,i,p,j) + d_q(m,i,p,j) + d_{pen}(m,i,p,j) + d'_s(m,i,p,j) + d'_q(m,i,p,j) \right\| + \alpha \sum_{(i,p,k)} s(i,p,k) \]

\( W(m,i,p,j) \): Weight for platoon of mode \( m \), intersection \( i \), and \( j \)th request for phase \( p \).

\( d_s(m,i,p,j) \): Signal delay for platoon \( (m,i,p,j) \) at current intersection \( i \).

\( d_q(m,i,p,j) \): Queue delay for platoon \( (m,i,p,j) \) at current intersection \( i \).

\( d'_s(m,i,p,j) \): Signal delay for platoon \( (m,i,p,j) \) at downstream intersection \( i_d \).

\( d'_q(m,i,p,j) \): Queue delay for platoon \( (m,i,p,j) \) at downstream intersection \( i_d \).

\( s(i,p,k) \): Green rest time for max out.

\( \alpha \): Weighting factor.
Test arterial: Speedway from Euclid to Alvernon

Test saturation rates: 0.3, 0.6, 0.8, 0.9, 1.0, 1.1, 1.2, corresponding to deterministic volume 1-7.

Test scenarios: Four sets of stochastic volumes generated by Normal distribution with mean from each deterministic volume.
PAMSCOD solution illustration:

1) Average cycle length compared with SYNCHRO optimized cycle length.
2) Partly coordination with bus priority under saturation rate 0.9 and high volume on Campbell.
Traffic control within a v2x environment –
PAMSCOD Simulation Performance

![Graph showing traffic control performance with different control methods]

- ASC Free
- ASC Coord
- PAMSCOD
- TSP Coord

Bus delay (veh/sec/phase) vs Demand (veh/hr)
## Traffic control within a v2x environment –
**PAMSCOD Simulation Performance**

- Delay decrease (%) from PAMSCOD to other methods.

<table>
<thead>
<tr>
<th>Methods</th>
<th>0.3</th>
<th>0.6</th>
<th>0.8</th>
<th>0.9</th>
<th>1</th>
<th>1.1</th>
<th>1.2</th>
<th>Average</th>
</tr>
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<td>Through put</td>
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</tr>
<tr>
<td>ASC Free</td>
<td>0.10%</td>
<td>0.04%</td>
<td>0.17%</td>
<td>2.13%</td>
<td>3.86%</td>
<td>3.36%</td>
<td>0.32%</td>
<td>1.43%</td>
</tr>
<tr>
<td>ASC Coord</td>
<td>-0.01%</td>
<td>0.00%</td>
<td>1.59%</td>
<td>6.81%</td>
<td>6.79%</td>
<td>5.39%</td>
<td>1.06%</td>
<td>3.09%</td>
</tr>
<tr>
<td>TSP Coord</td>
<td>0.11%</td>
<td>0.21%</td>
<td>2.54%</td>
<td>13.86%</td>
<td>11.68%</td>
<td>13.14%</td>
<td>7.92%</td>
<td>7.07%</td>
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<td>Avg. all delay</td>
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<tr>
<td>ASC Free</td>
<td>-28.85%</td>
<td>-6.63%</td>
<td>10.33%</td>
<td>32.61%</td>
<td>36.28%</td>
<td>38.13%</td>
<td>46.13%</td>
<td>18.28%</td>
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<tr>
<td>ASC Coord</td>
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<td>3.54%</td>
<td>6.88%</td>
<td>12.35%</td>
<td>1.79%</td>
<td>-0.56%</td>
<td>2.11%</td>
<td>5.44%</td>
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<tr>
<td>TSP Coord</td>
<td>37.36%</td>
<td>42.23%</td>
<td>60.12%</td>
<td>63.44%</td>
<td>38.50%</td>
<td>19.72%</td>
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<td>Avg. bus delay</td>
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<td>ASC Free</td>
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<td>21.16%</td>
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<td>ASC Coord</td>
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<td>42.58%</td>
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<tr>
<td>TSP Coord</td>
<td>-2.61%</td>
<td>-7.12%</td>
<td>-11.44%</td>
<td>12.34%</td>
<td>10.49%</td>
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</table>
MCDOT SMARTDrive Program

- MCDOT/ADOTE-Connected Priority Applications
  - EV Traffic Signal Priority
  - Transit Traffic Signal Priority
  - Incident Warning
  - Traffic Performance Monitoring

- Pooled Fund Study
  - Multi-Modal Intelligent Traffic Signal System
    - UA + PATH
    - Savari
    - Kapsch
    - Econolite
    - SCSC
    - Volvo Technologies

- SBIR Projects (Savari)
  - InFusion
  - SmartCross

Test Network

Anthem, AZ
Connected Vehicle Applications for Emergency Responders

Traffic Signal Priority
- Multiple Requests
- GPS Intersection Map
- DSRC 2-way communications between vehicles and signal (V2I)

US DOT Standards
- NTCIP 1202, 1211
- IEEE 802.11p, 1609 and SAE J2735
- ISO TC204

Ramp Meter Priority
- GPS Ramp Map
- DSRC 2-way communications between vehicles and controller (V2I)

Ad-Hoc Warning Beacon
- GPS Roadway Map
- DSRC communications between vehicles and vehicles (V2V)

AZ511 Information via Backhaul
Pooled Fund Study

- Eleven Members (States and Local Agencies)
- Focus on Developing Strategies and Path for Connected Vehicle Infrastructure deployment
- Equipment Certification Program
- Multi-modal Intelligent Traffic Signal System
  - Intelligent Traffic Signal System (ISIG)
  - Transit Signal Priority (TSP)
  - Mobile Accessible Pedestrian Signal System (PED-SIG)
  - Emergency Vehicle Preemption (PREEMPT)
  - Freight Signal Priority (FSP)
- Commercial Vehicle Applications (future)
SBIR: Augmenting Inductive Loop Vehicle Sensor Data with SPAT and GrID via Data Fusion

- InFusion: Performance Improvements of Traffic Controllers by means of Data Fusion and Analysis
- Savari Networks, Inc. (Prime)
- Team
  - Subcarrier Systems Corp. (SCSC) (David Kelley)
  - UA (Larry Head)
  - Phase I Completed, Phase II Proposal in Development
SBIR: InFusion - Overview

Savari Networks, Inc.
SBIR: InFusion – Simulation Testing

VISSIM – Hardware in the Loop Simulation

MAP – J2735 Specified (Kelley)
Moving Objects – Tracked for Control Algorithms

Savari Networks, Inc.
SBIR: Smartphone Signal Alert Status

- **SmartCross – Traffic Signal Interface on the Smartphone**
- **Savari Networks, Inc. (Prime)**

**Team**
- Subcarrier Systems Corp. (SCSC) (David Kelley)
- UA (Larry Head)
- Phase I Completed (Final Report under Review)

**Goal**
- a proof of concept system that demonstrates how smartphones can be used securely to enhance pedestrian safety

Savari Networks, Inc.
SBIR: SmartCross - Overview

1. RSE Broadcasts SPaT and MAP messages
2. Equipped vehicles and pedestrians broadcast BSMs
3. Public vehicles may request priority/preemption

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Savari Networks, Inc.
SBIR: SmartCross GUI

- Walk Interval
- Flashing Don’t Walk Interval
Summary

• Developed a model that provides priority control at traffic signals that considers
  – Coordination
  – Uncertainty (Robust)
  – Actuations
  – Network Extension

• Consideration for multiple modes of travelers

• Unified Framework for Real-Time Decision Making
Questions?
Lessons Learned

• DSRC – Highly reliable
• Two-way communication between vehicles and infrastructure
  – Infrastructure addresses multiple vehicle arrivals intelligently
  – Vehicles know about other vehicles (feedback)
• Standards
  – J2735 and NTCIP
DSRC Experience

DSRC range
Feb. 20, 2010

626.53m

440.86m

355.48m

>>291.55m
DSRC Experience