The Multi Modal Intelligent Transportation System (MMITSS): Connected Vehicle Capabilities for Transit/Streetcars

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American Public Transportation Association
Streetcar Subcommittee
2019 Mid-Year Meeting
**Connected Vehicles**

- **Purpose:**
  - Safety
  - Mobility
  - Environment

- **Basic Safety Message (BSM)**
  - Temporary ID (ensure privacy)
  - Position (GPS)
  - Motion
    - Speed
    - Heading
    - Steering Wheel Angle
    - Acceleration
  - Brakes
  - Vehicle Size
  - Mode (vehicle, transit, truck, EV,...)

**DSRC 5.9 GHz Wireless**

*Basic Safety Message (SAE J2735 BSM)*
Broadcast 10 times/second (10 HZ)
Connected Vehicles and Infrastructure Systems

On Board Unit (OBU)
After Market Safety Device (ASD)

Vehicle(s)...

+ Connected Vehicle Equipment

Connected Vehicle Infrastructure Equipment
Road Side Unit (RSU)

DSRC 5.9 GHz Radio
- BSM/SRM
- Signal Phase and Timing (SPaT)
- MAP

Cooperative Applications:
- Transit Priority
- Truck Priority
- Emergency Vehicle Priority

MAP Data
Digital Description of Roadway

(D. Kelley, 2012)
Connected Vehicles
Technology, Equipment and Standards

5.9 GHz DSRC Wireless
IEEE 1609

SAE J2735 Message Set
SAE J2945/0 Minimum Performance
Requirements

5.9 GHz DSRC Roadside Unit (RSU)

Connected Vehicle Infrastructure Equipment
Road Side Unit (RSU)

Ethernet IEEE802.3

DSRC Roadside Unit (RSU)
Specifications Document v4.1
(USDOT October 31, 2016)
The Multi Modal Intelligent Traffic Signal System Program

Funded as Connected Vehicle Pooled Fund Project (FHWA, MCDOT, Caltrans, VDOT, FDOT, MnDOT, TxDOT,...)

- University of Arizona
  - Larry Head (PI)
  - Sherilyn Keaton (Software Manager)
  - GRA: Niraj Altekar, Debashsis Das
  - National Academies: Medhi Zamanapour (FHWA, PhD 2016)
- PATH/UC Berkeley
  - Kun Zhou (co-PI)
  - Huadong Meng (Research Engr)
  - John Spring (Software Engr)
  - David Nelson (Hardware Engr)
- Maricopa County DOT
  - Faisal Saleem, April Wire, LeShawn Charlton
- California DOT
  - Greg Larson
MMITSS Basic Concepts

Section 1
- Priority for
  - Freight

Priority Hierarchy
- Rail Crossings
- Emergency Vehicles
- Freight
- Coordination
- Transit
  - BRT
  - Streetcar
  - Express
  - Local (Late)
- Passenger Vehicles
- Pedestrians

Traffic Control System
MMITSS Basic Concepts

Priority Hierarchy
- Rail Crossings
- Emergency Vehicles
- Transit
  - Streetcar
  - BRT
  - Express
  - Local (Late)
- Pedestrians
- Passenger Vehicles
- Freight

Section 2
- Priority for
  - Streetcar
  - Pedestrians

A Traffic Control System
Real-Time Performance Measures – by **MODE**, by movement

- Volume (mean, variance)
- Delay (mean, variance)
- Travel Time (mean, variance)
- Throughput (mean, variance)
- Stops (mean, variance)
MMITSS Priority Control

- Integrated approach to Signal Control and Prioritization
- Consistent with NTCIP SCP 1211 Standard (2014)

Key Features
- Accommodate Multiple Active Priority Requests from Different Modes
  - N-Level Priority Hierarchy
- Coordination within the Priority Control Framework
MMITSS Architecture
MMITSS Characteristics

- Uses Connected Vehicle Data
  - BSM, MAP, SRM, SSM, (SPaT)
- ISIG: Adaptive Control
  - RT-TRACS, RHODES, COP, OPAC,…
- PRIORITY (EVP, TSP, FSP): Priority Request Server (MRP)/Generator (OBU)
  - NCHRP 3-66, NTCIP 1211
- PEDSIG
  - Smartphone APP
Development

MMITSS (AZ) Software Architecture

[Diagram showing the software architecture with components and arrows indicating data flow]
Basic Operational Concept: Priority Control

- When a [streetcar] vehicle enters/remains in the range of an RSU
  1. Hears (Listens for...)
     - MAP/SPaT
     - WAVE Service Announcement (go to channel XX to talk)
  2. Computes Position on MAP, Desired Service Time (ETA), Desired Ingress and Egress (known for streetcar!)
  3. Sends a Signal Request Message (SRM)
  4. Receives Signal Status Message (SSM* - confirmation)
  5. Passes through intersection
  6. Sends a Cancel Signal Request Message (SRM)

Additional Details
Arizona Connected Vehicle Test Bed
Anthem, AZ

DSRC Installations:
11 Signalized Intersection
6 Freeway Interchanges
10 Freeway Locations

Approx. 25,000 Residents
Approx. 10,000 Vehicles

1Expansion Project (ADOT)
Freight Signal Priority (FSP) - Simulation

- MC-85 Maricopa County
  - 19 Signalized Intersection
FSP: Simulation Estimates of Benefits (with MMITSS at 8/19 Signals)

- Reduced Stops by 20%
  - Reduce the Impact on Pavement
  - Reduce acceleration – Improved Air Quality
  - Less Delay

- Improved “Smoothness” of Traffic Flow
The “Impact” of Connected Vehicles/MMITSS

- MMITSS Project Discussion/Plan
- MMITSS Project Proposal Developed
- MMITSS Project Active
Portland Deployment

- Deploy on the “Art Museum Corridor”
- 2 streetcars, 4 intersections
- Simple goals: get the hardware installed, functioning; get data transferring to PORTAL; build initial analytics

Portland State University
City of Portland
University of Arizona
MMITSS Project Status

✓ Phase 1: Concept of Operations, Requirements and High Level Design
  ✓ March 2012 – March 2013
  ✓ Produced Concept of Operations, Requirements Document and High Level Design Document

✓ Phase 2: System Development, Deployment and Field Test
  ✓ October 2013 – April 2015
  ✓ Developed MMITSS-AZ and MMITSS-CA
  ✓ Conducted Field Demonstrations and Impact Assessment of MMITSS-AZ (Leidos)
  ✓ Software available through USDOT OSADP ([https://www.itsforge.net/index.php/community/explore-applications#/30/63](https://www.itsforge.net/index.php/community/explore-applications#/30/63))

• Phase 3: Deployment Readiness Enhancements
  • February 2018 – July 2019
  • Improve software maturity, deployment support, user support
  ✓ MMITSS Development Group (MDG) for open source development community
Other v2i Applications

- School Zone Alert!
- Construction Zone Alert!
- Intelligent Traffic Signal System
- Emergency Vehicle Alert!
- Incident Ahead Alert!
V2V - Emergency Vehicle Alert

- V2X Communication of Location/Speed of Emergency Vehicles
- In-vehicle Alert
  - "Behind You"
  - "Approaching Intersection from Left"
  - ...
Challenges and Opportunities

• Challenge: FCC Allocation of 5.9GHz Spectrum is under attack
  • WIFI Industry wants to stream movies and have more WIFI access
  • 5GAA wants to use part of the spectrum for deployment of LTE (they call it 5G, but let's be honest)
    • We aren't using the spectrum to its full advantage
  • Office of Management and Budget (OMB) moved the NHTSA Mandate to a long term priority (no new regulations or to get one, remove two)

• Opportunity: DSRC is in FCC regulations. Legally it is the only available solution
  • It works
  • It is effective
  • We can deploy!
Questions?
Discussion

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• Backup Slides for MMITSS
Traffic Control Terminology

Movements
Phases
Detectors

Fixed Time
Actuated
Coordinated
Coordinated-Actuated

Dual Ring, 8-Phase Controller
A Core Logic Model

Dual Ring Controller (Core Logic)

Cycle 1

Cycle 2

Precedence Diagram

(works 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>
<th>Recall Omit, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>☒ ☒ ☒ ☒ ☒</td>
<td></td>
</tr>
</tbody>
</table>

Timing Values

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

Precedence Network Model

Real-time Demand parameters

Priority requests
- Vehicle/ped calls
- Preemption calls
- Advanced detection data
Requests for Priority

- Preemption
  - Heavy Rail
  - Emergency Vehicles*

Priority
- Buses
- Pedestrians
- Trucks
- Special Vehicles
- Evacuation

Request for Phase 8 at \( t=38 \)

\[ R^1_8 = 38 \]

\[ \text{Cycle 1} \]
\[ \text{Cycle 2} \]
Multiple Requests for Priority

There could be many requests from many vehicles
Model Formulation

\textit{Minimize} \quad \text{Total Priority Delay + Vehicle Cost}

\textit{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 = $\theta^j_c, \theta^j_s \in \{0,1\}$, phase and interval skipping = $S^{__j}_p \in \{0,1\}$
Precedence Constraints

\[ t_1^1 = 0 \]
\[ t_5^1 = 0 \]
\[ t_2^k = t_1^k + v_{1}^k \]
\[ t_6^k = t_5^k + v_{5}^k \]
\[ t_3^k = t_2^k + v_{2}^k, \quad t_3^k = t_6^k + v_{6}^k \]
\[ t_7^k = t_2^k + v_{2}^k, \quad t_7^k = t_6^k + v_{6}^k \]
\[ t_4^k = t_3^k + v_{3}^k \]
\[ t_8^k = t_7^k + v_{7}^k \]
\[ t_{1}^{k+1} = t_4^k + v_{4}^k, \quad t_{1}^{k} = t_8^k + v_{8}^k \]
\[ t_{5}^{k+1} = t_4^k + v_{4}^k, \quad t_{5}^{k} = t_8^k + v_{8}^k \]

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

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

\[
\begin{align*}
    t_p^k & \geq 0, \\
    g_p^k(\Omega, \Phi, \omega, s_p^k) & \leq g_p^k \leq g_p^k(\Omega, \Phi, \omega, s_p^k), 
\end{align*}
\]

for all \(p\) 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
\(s_p^k\) are binary interval decision variables (skip, don't skip)
Phase Interval Constraints

\[ g_p = \max \left\{ \left( D \min_p \cdot (1 - X \min R_p) \right), \left( D_{\text{amin}} \cdot C_{\text{phs}} (1 - S \min_p) \right), \left( (Dw_p + Dfdw_p) \cdot C_{\text{ped}} \cdot (1 - S \text{ped}_p) \right), D \max_p \cdot X \max R_p \right\} \bullet (1 - S C_p^k) \bullet (1 - X \text{omit}_p) \]

\[ \overline{g}_p = \left\{ \max \left( D \max_p, (Dw_p + Dfdw_p) \cdot C_{\text{ped}} \right) \right\} \bullet (1 - S C_p^k) \bullet (1 - X \text{omit}_p) \]

Notation

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

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

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

\[ \sum_{k} \theta_{p,e}^{j,k} + \theta_{p,s}^{j,k} = 1 \]
for every priority request \( R^j_p \)
Service Phase Selection

Constraints

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

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

Minimize \( D = \sum_{(p,j)} \sum_k \theta_{p,e}^{j,k} \left( t_p^k - R_p^j \right) \)
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

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

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

<table>
<thead>
<tr>
<th>Data:</th>
<th>( R_{jp} \quad g_{pk}^{\text{min}} \quad g_{pk}^{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable:</td>
<td>( D_{jpk} \quad t_{pk} \quad g_{pk} \quad \theta_{jpk} )</td>
</tr>
</tbody>
</table>

Equality

\[ Et^1 = 0 \]

Serving cycle selection constr.

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.

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

Dual-ring, eight-phase controller
Serving Priority Requests – Phase Time Diagram

- Request for Phase 2 at Time 50
- Request for Phase 8 at Time 60
- Request for Phase 3 at Time 120
- Request for Phase 2 at Time 170
Serving Priority Requests – Phase Time Diagram

Request for Phase 2 at Time 50

Request for Phase 8 at Time 60

Request for Phase 7 at Time 120

Request for Phase 2 at Time 170
Flexible Implementation Algorithm (Zamanipour et al., 2016)

• Critical points for one request

CLP1: \( \max \{FL1, BL3\} \)
CLP2: \( \max \{FL2, BL2\} \)
CLP3: \( \max \{FL3, BL1\} \)
CLP4: BR1

CRP1: \( \min \{FR1, BR4\} \)
CRP2: \( \min \{FR2, BR3\} \)
CRP3: \( \min \{FR3, BR2\} \)
CRP4: BR1

< Zamanipour’s Ph.D final defense slide>
Field Testing Scenarios, March 3rd and 4th: Designed and Conducted by Leidos (IA Contractor)

- 2 trucks with priority in northbound/southbound
- 2 buses with priority in eastbound/westbound
- 10 rounds of testing
- 6 regular vehicles

Source: Leidos Field Test Plan
Field Test Result for Transit Priority

### Transit #1

<table>
<thead>
<tr>
<th>Round</th>
<th>TT (sec)</th>
<th>With Priority</th>
<th>Without Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2</td>
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<td>10</td>
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</tbody>
</table>

### Transit #2

<table>
<thead>
<tr>
<th>Round</th>
<th>TT (sec)</th>
<th>With Priority</th>
<th>Without Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>10</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Baseline (2 buses without Priority Requests for 10 Round Trips)</th>
<th>TSP (2 buses with Priority Requests for 10 Round Trips)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average TT (sec)</td>
<td>850.12</td>
<td>762.56</td>
<td>-10.3</td>
</tr>
<tr>
<td>TT Standard Deviation</td>
<td>91.13</td>
<td>53.48</td>
<td>-41.3</td>
</tr>
</tbody>
</table>
Time-Space Diagram without MMITSS

- Daisy Mountain and Gavilan Peak Northbound Movement
- Number of Stops: 5, Number of Queue Encounters: 1
- Using BSMs sent from Truck #1

Truck #1
Wednesday Afternoon: 1:30 pm - 5:00 pm
Time-Space Diagram with MMITSS

- Daisy Mountain and Gavilan Peak Northbound Movement
- Number of Stops: 1, Number of Queue Encounters: 2
- Using BSMs sent from Truck#1
Findings for Freight Priority

### Trucks #1

<table>
<thead>
<tr>
<th>Round</th>
<th>With Priority</th>
<th>Without Priority</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

### Trucks #2

<table>
<thead>
<tr>
<th>Round</th>
<th>With Priority</th>
<th>Without Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>FSP</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average TT (sec)</strong></td>
<td>182.42</td>
<td>175.44</td>
<td><strong>-3.84</strong></td>
</tr>
<tr>
<td><strong>TT Standard Deviation</strong></td>
<td>36.28</td>
<td>28.37</td>
<td><strong>-21.78</strong></td>
</tr>
</tbody>
</table>
MMITSS Pedestrian Smartphone App

Savari SmartCross (SBIR) Application Architecture

Allows Pedestrian to receive auditory and haptic feedback
- Align with Crosswalk
- Send Call for Service
- Be given WALK
- PedCLEAR Countdown

Sara Khosravi, PhD Student

Traffic Signal Controller → NTCIP over Ethernet → Road Side Equipment

Ethernet → (WiFi) → (3G/4G) → Application on Smartphone → Cloud Service
Latency vs. Communications Technologies For IntelliDrive℠

Active Safety Latency Requirements (secs)
- Traffic Signal Violation Warning: 0.1
- Curve Speed Warning: 1.0
- Emergency Electronic Brake Lights: 0.1
- Pre-Crash Sensing: 0.02
- Cooperative Forward Collision Warning: 0.1
- Left Turn Assistant: 0.1
- Lane Change Warning: 0.1
- Stop Sign Movement Assistance: 0.1

Least stringent latency requirement for Active Safety (1 sec)
Most Stringent latency requirement for Active Safety (.02 sec)

Communications Technologies

- 5.9 GHz DSRC (.0002 secs)
- Two-Way Satellite (60+ secs)
- Terrestrial Digital Radio & Satellite Digital Audio Radio (10 - 20 secs)
- WiFi 802.11 (3 - 5 secs)
- Bluetooth (3 - 4 secs)
- Cellular (1.5 - 3.5 secs)
- WiMax (1.5 - 3.5 secs)

Note: Y-axis not to scale for illustration purposes

From US DOT Briefings on Connected Vehicle

Data source: Vehicle Safety Communications Project – Final Report
WAVE Communications