# 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**

THE UNIVERSITY OF ARIZONA



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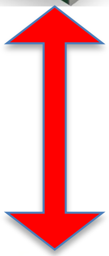
# Connected Vehicles


DSRC
5.9 GHz Wireless

Basic Safety
Message
(SAE J2735 BSM)
Broadcast 10
times/second
(10 HZ)

- 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,…)

# Connected Vehicles and Infrastructure Systems


Vehicle(s)…

+

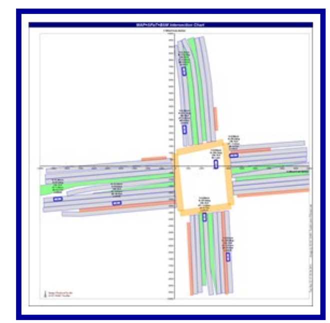
Connected Vehicle Equipment


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

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

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


Connected Vehicle Infrastructure Equipment Road Side Unit (RSU)



MAP Data
Digital Description of Roadway

(D. Kelley, 2012)

# Connected Vehicles

## Technology, Equipment and Standards

SAE J2735 Message Set
SAE J2945/0 Minimum Performance Requirements

5.9 GHz DSRC Wireless
IEEE 1609

Ethernet IEEE802.3

Connected Vehicle
Infrastructure Equipment
Road Side Unit (RSU)

NTCIP 1202, 1211 Messages

**DSRC Roadside Unit (RSU) Specifications Document v4.1 (USDOT October 31, 2016)**

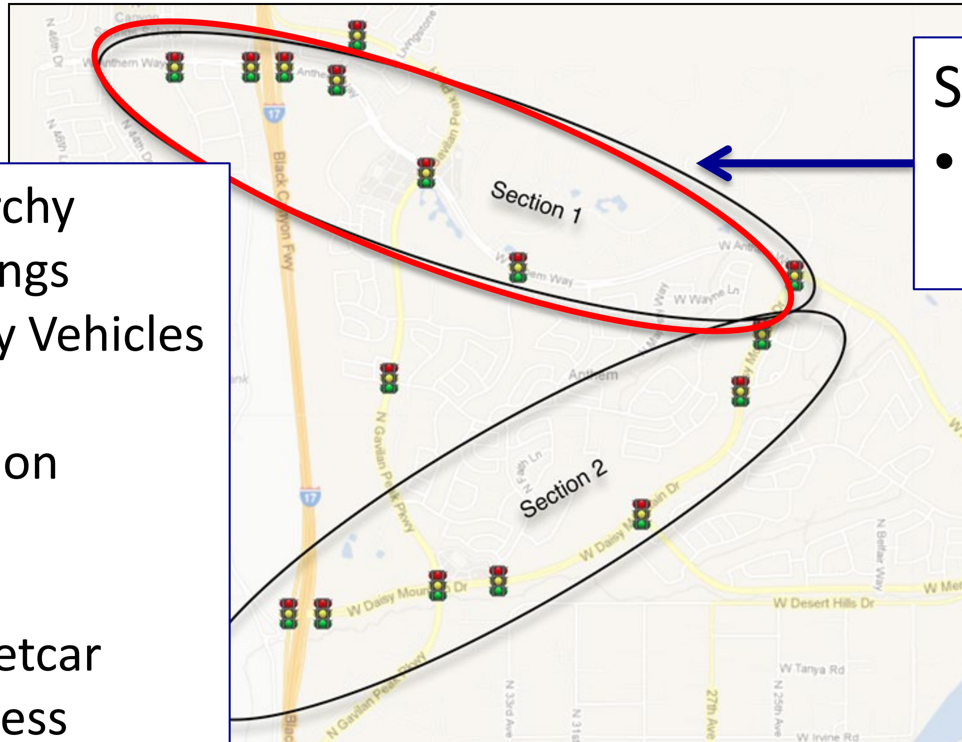
# The Multi Modal Intelligent Traffic Signal System Program

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

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

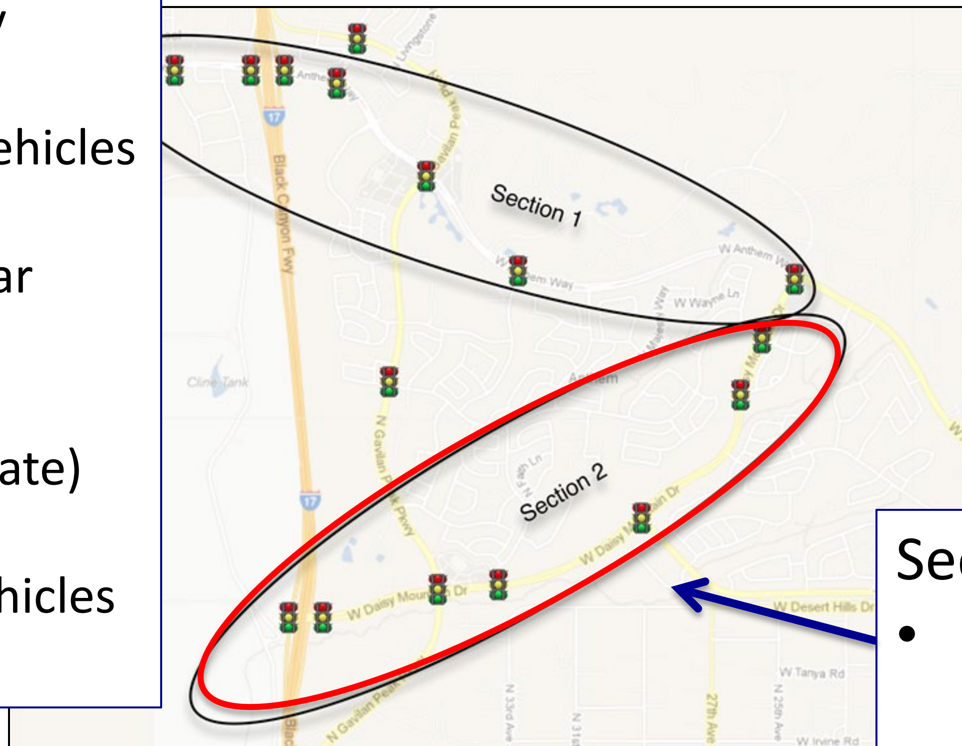



Section 1
- Priority for
  - Freight

Traffic Control System

# MMITSS Basic Concepts

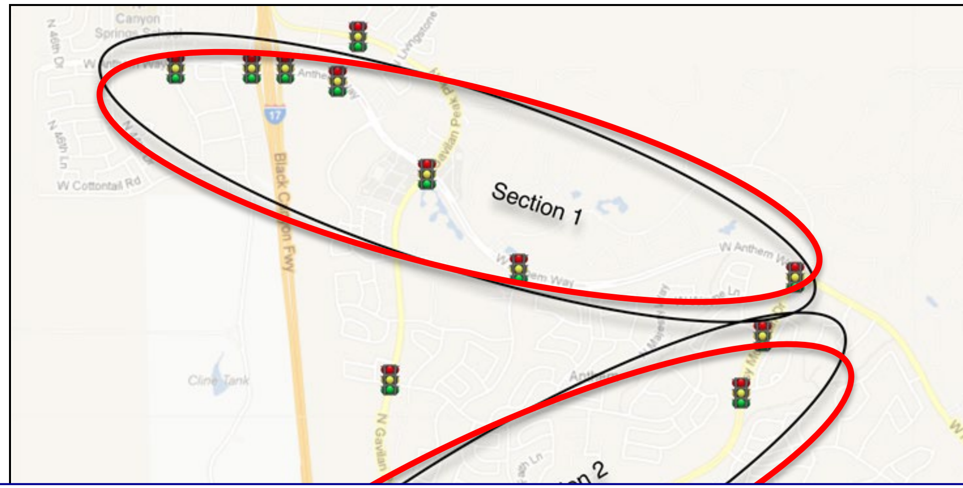
Priority Hierarchy
- Rail Crossings
- Emergency Vehicles
- Transit
  - Streetcar
  - BRT
  - Express
  - Local (Late)
- Pedestrians
- Passenger Vehicles
- Freight




A Traffic Control System

Section 2
- Priority for
  - Streetcar
  - Pedestrians

# MMITSS Basic Concepts




Real-Time Performance Measures – by **MODE**, by movement

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

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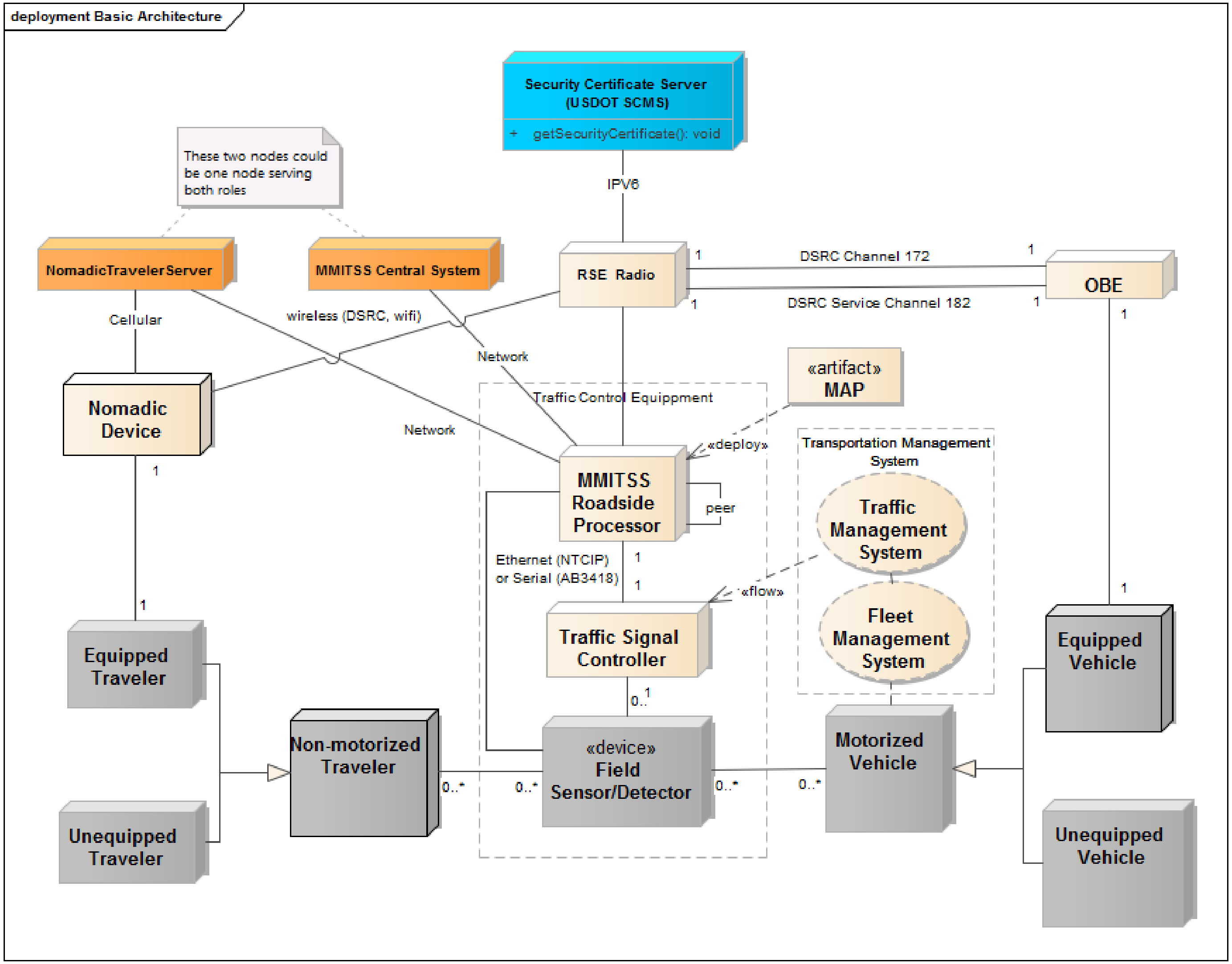
# MMITSS Priority Control

- 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

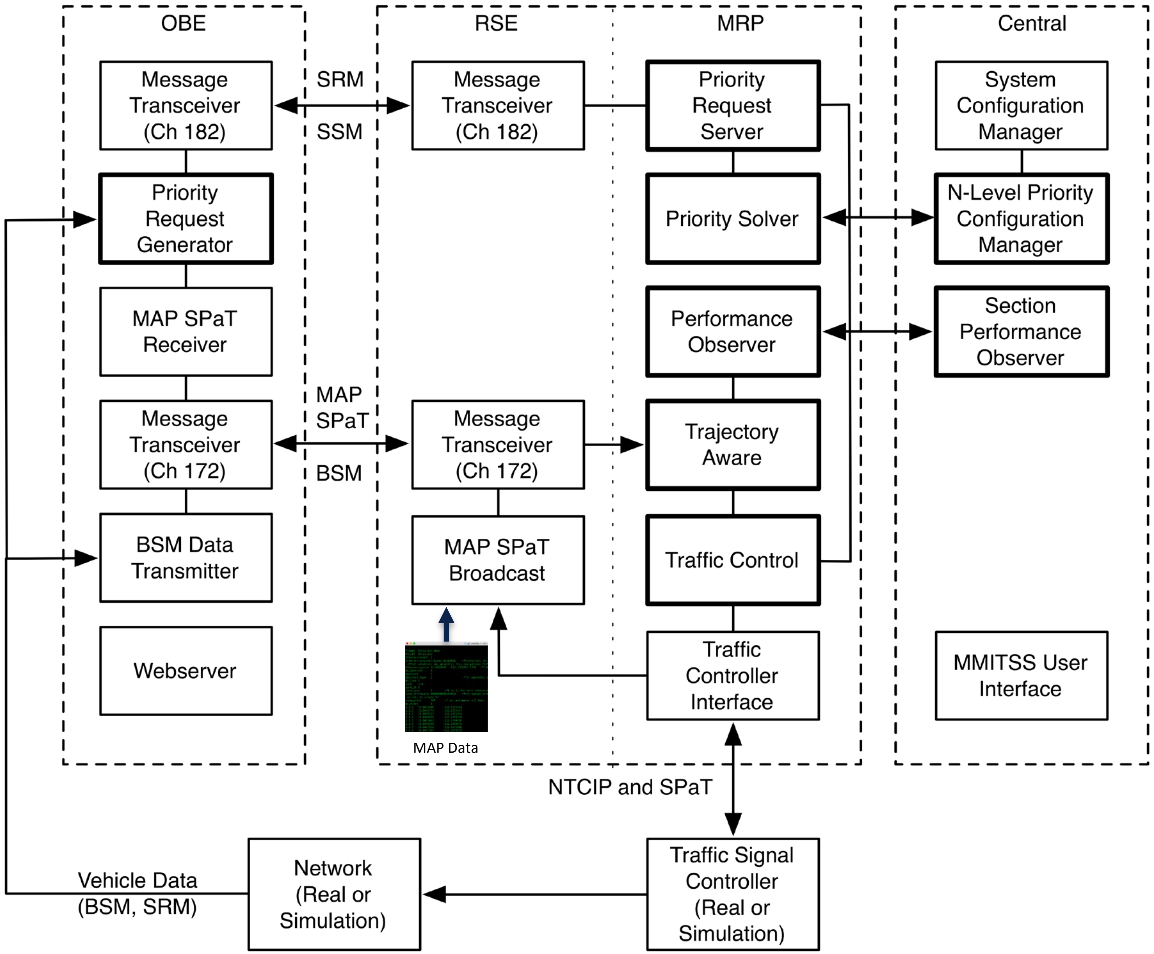
# MMITSS Architecture



# 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

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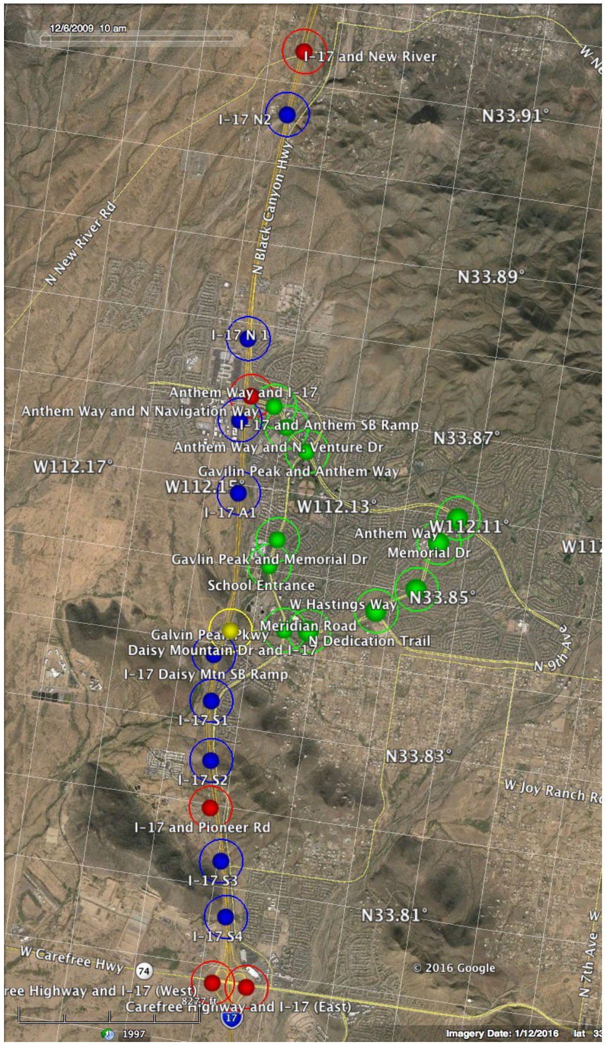
# Basic Operational Concept: Priority Control

- 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[1]

10 Freeway Locations[1]

Approx. 25,000 Residents

Approx. 10,000 Vehicles



[1]Expansion Project (ADOT)

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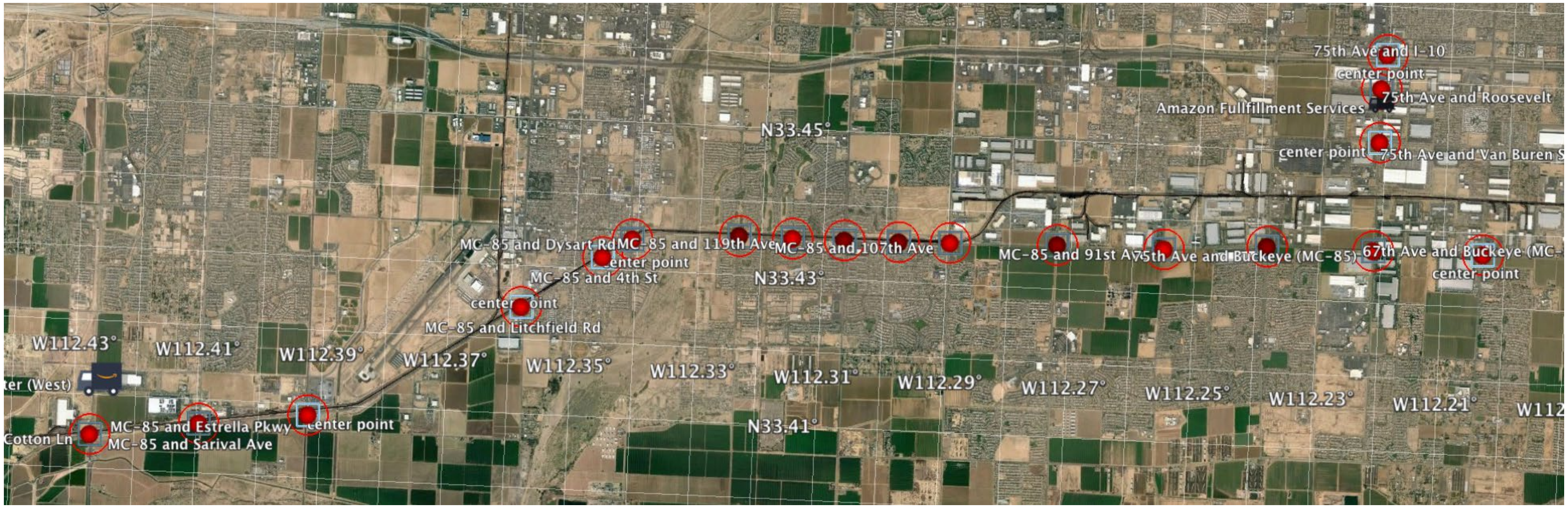
# Freight Signal Priority (FSP) - Simulation

- MC-85 Maricopa County
  - 19 Signalized Intersection

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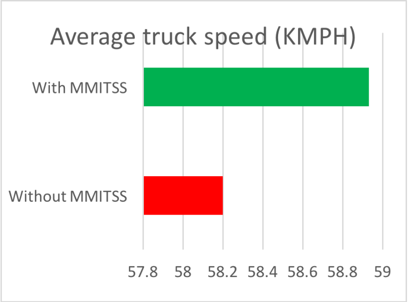
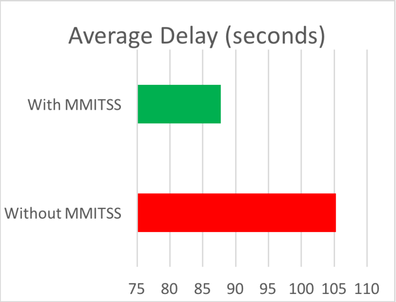
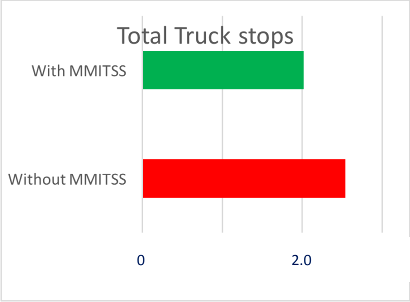
# FSP: Simulation Estimates of Benefits (with MMITSS at 8/19 Signals)

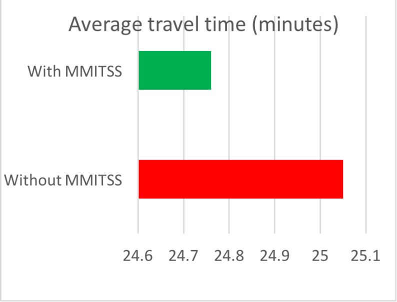
- Reduced Stops by 20%
  - Reduce the Impact on Pavement
  - Reduce acceleration – Improved Air Quality
  - Less Delay

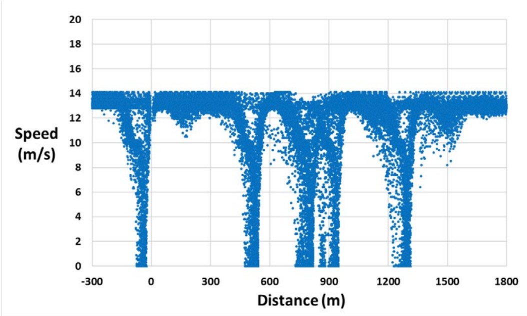
- Improved “Smoothness” of Traffic Flow

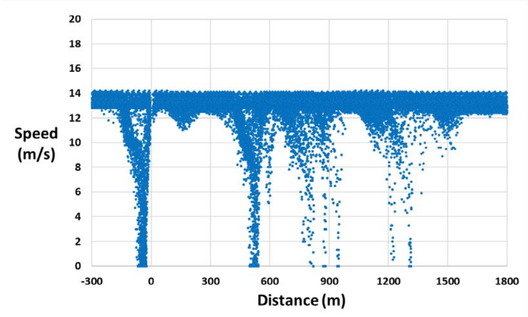
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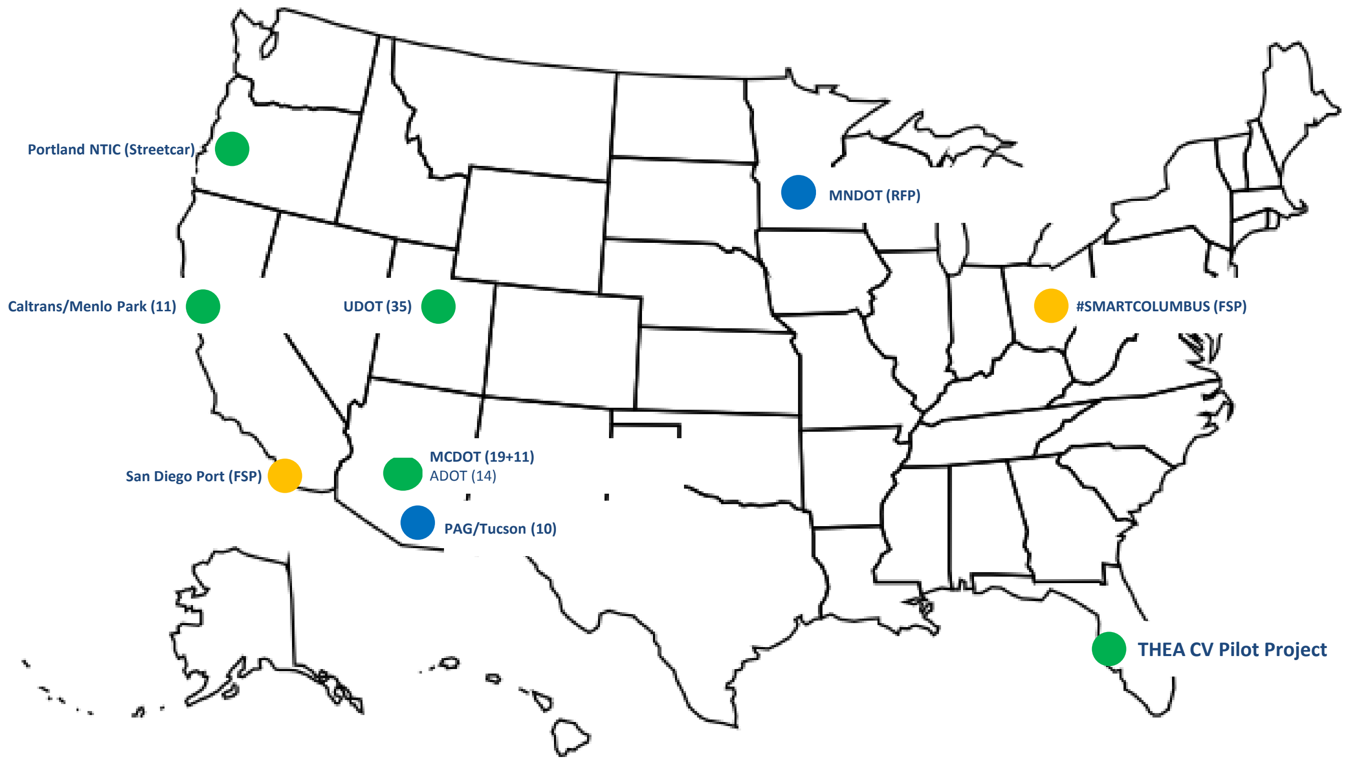
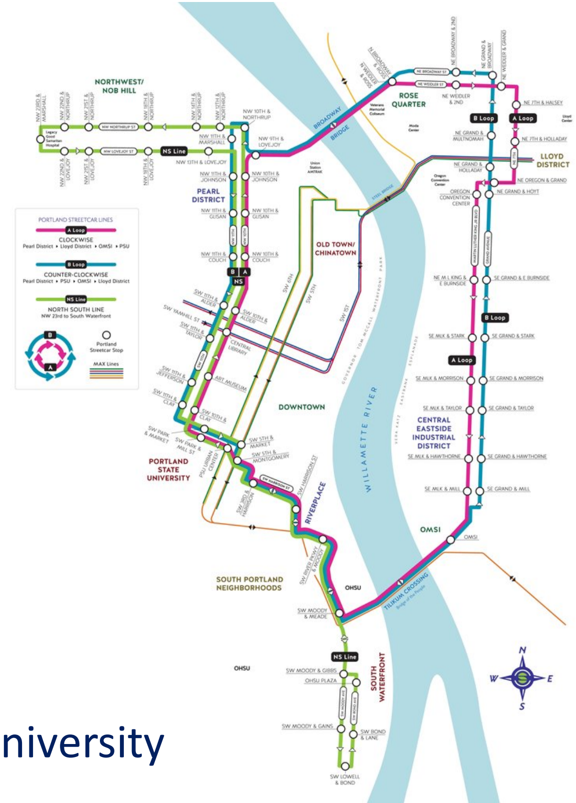
# The "Impact" of Connected Vehicles/MMITSS




- 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




NITC
NATIONAL INSTITUTE for TRANSPORTATION and COMMUNITIES

Portland State University
City of Portland
University of Arizona

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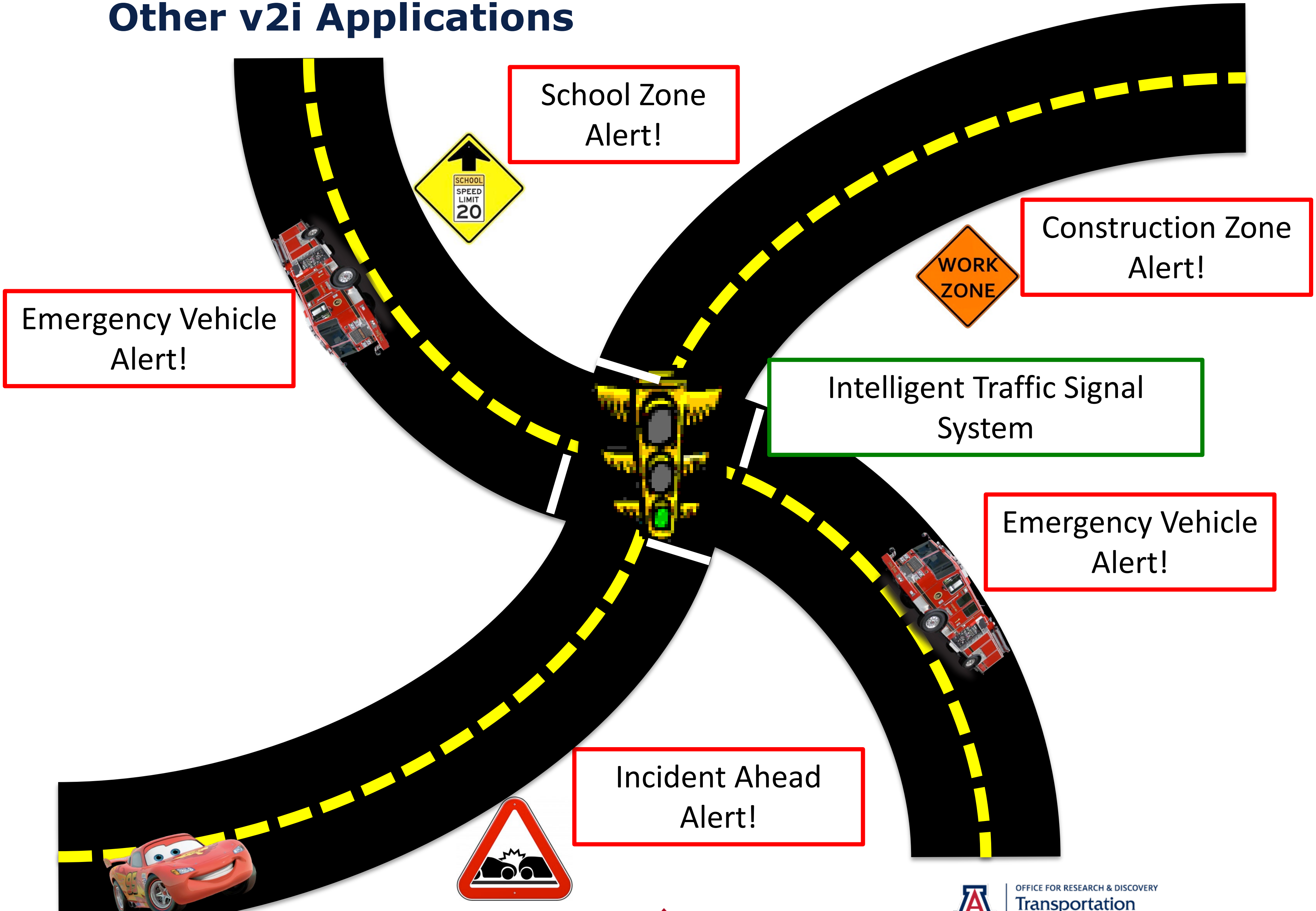
# MMITSS Project Status

- ✓ 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
  - ✓ http://www.cts.virginia.edu/cvpfs_research/
- ✓ 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)

- 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

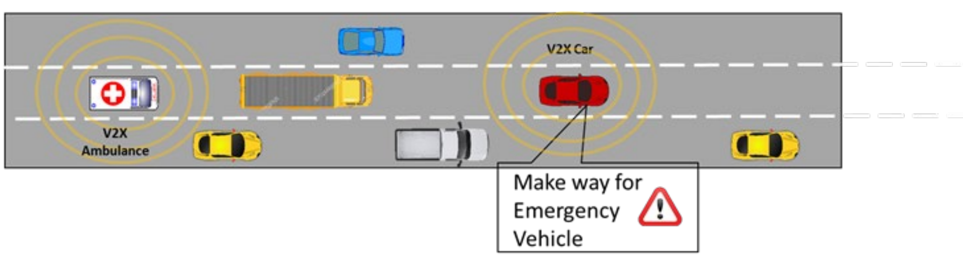
# Other v2i Applications



# V2V - Emergency Vehicle Alert

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


Houston, TX, March 30, 2009



# 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 lets 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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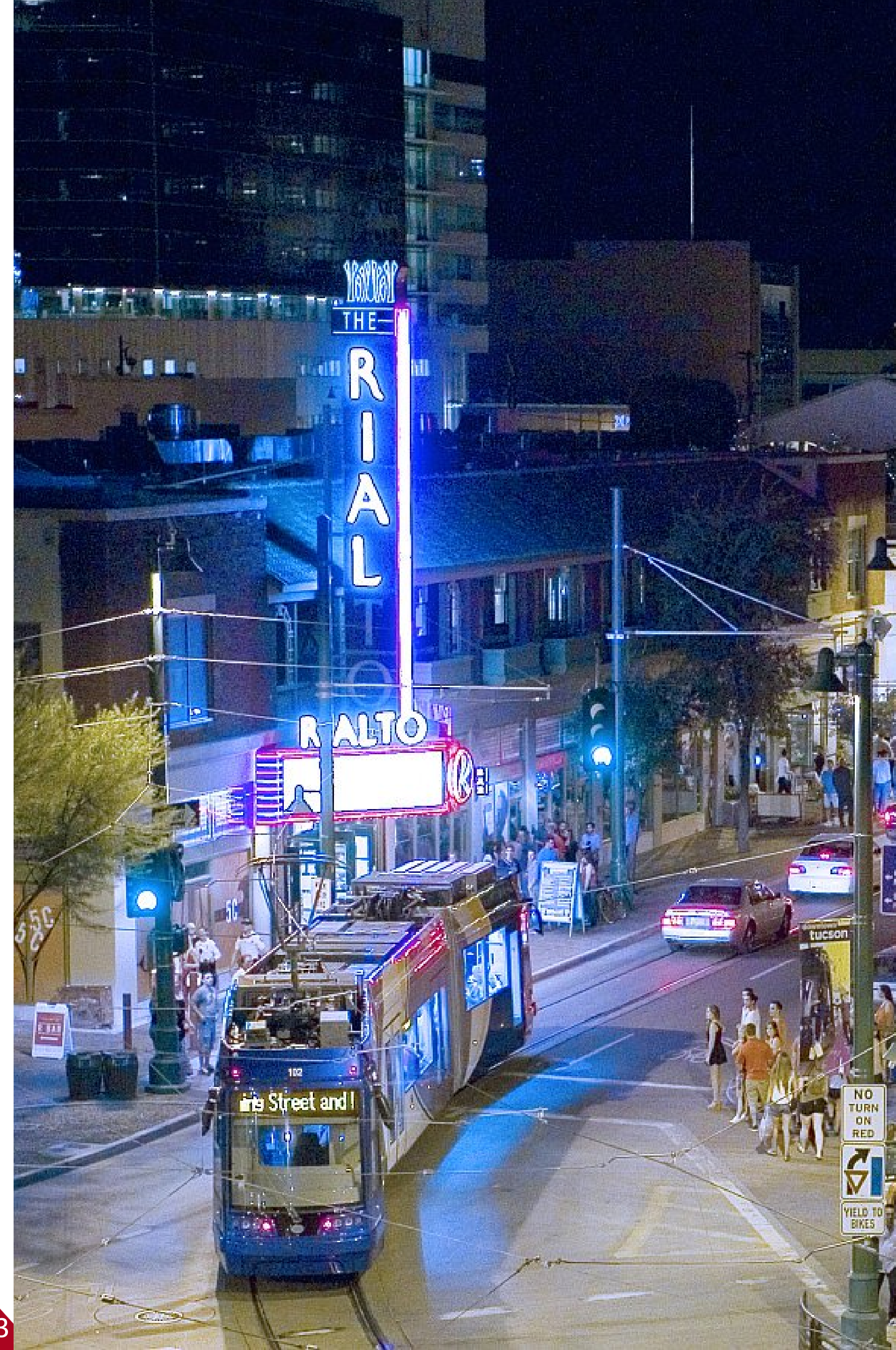
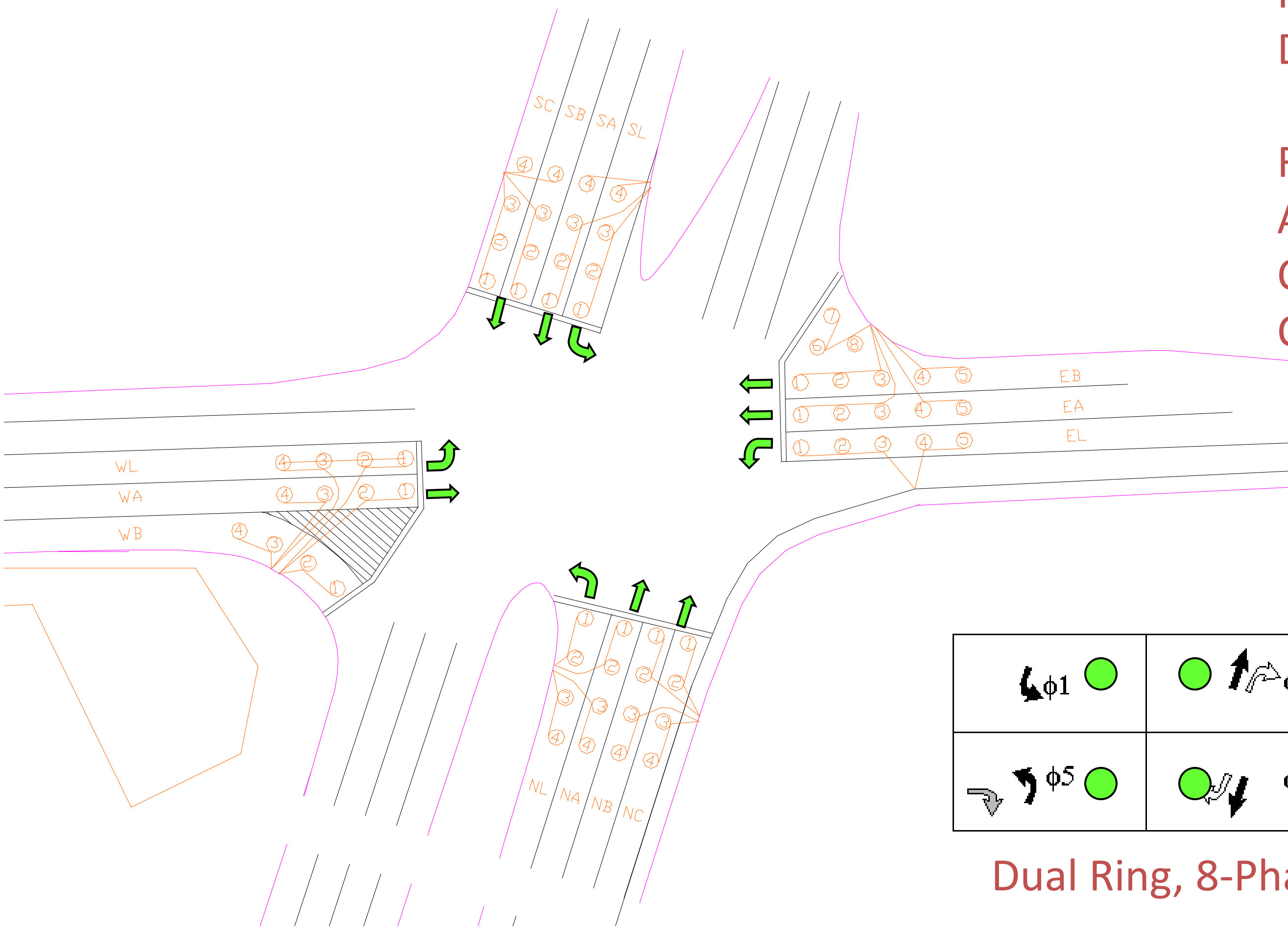


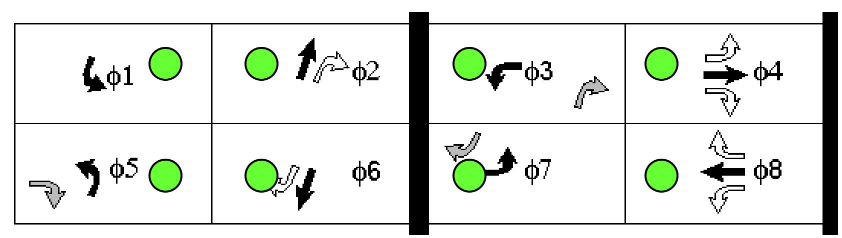
- Backup Slides for MMITSS

# Traffic Control Terminology




Movements
Phases
Detectors

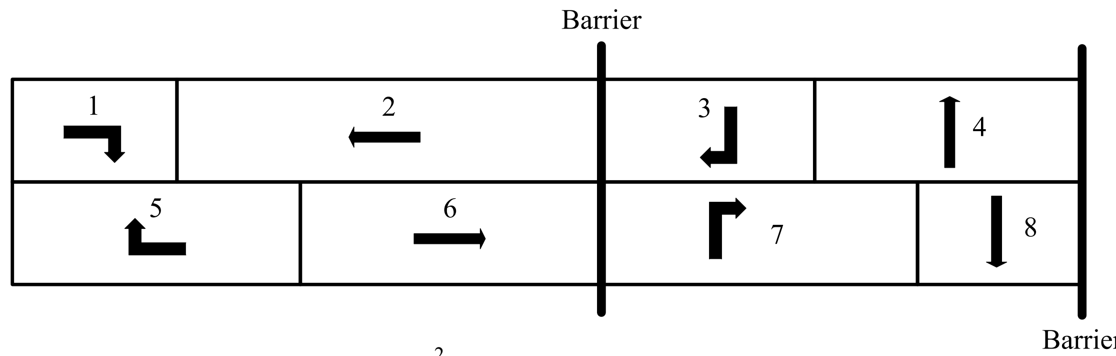
Fixed Time
Actuated
Coordinated
Coordinated-Actuated

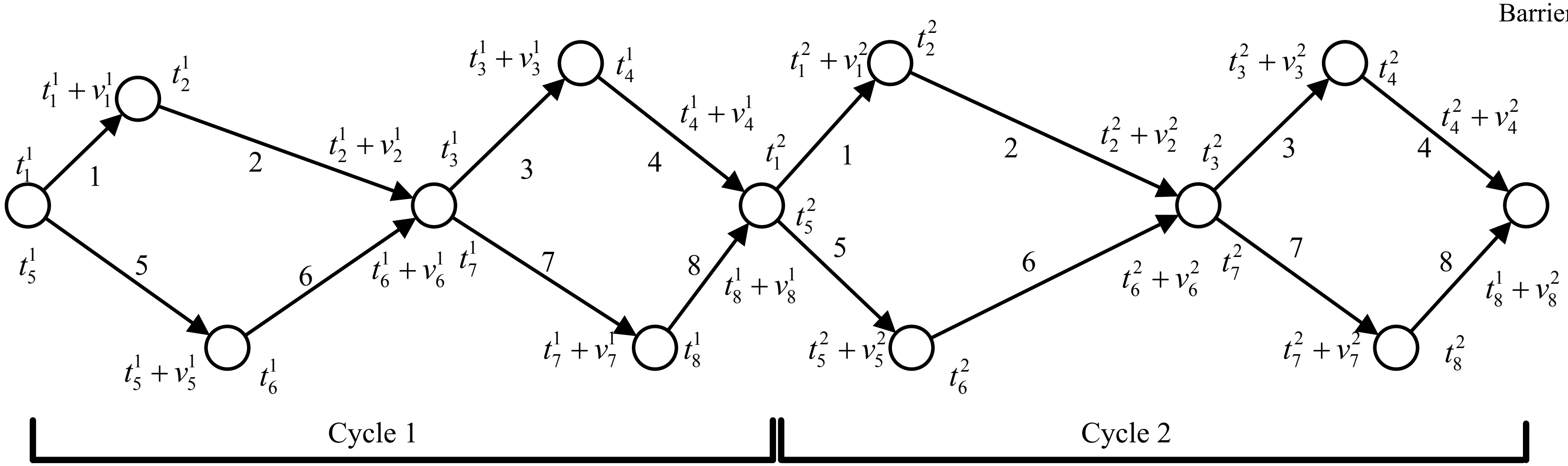



Dual Ring, 8-Phase Controller

# A Core Logic Model

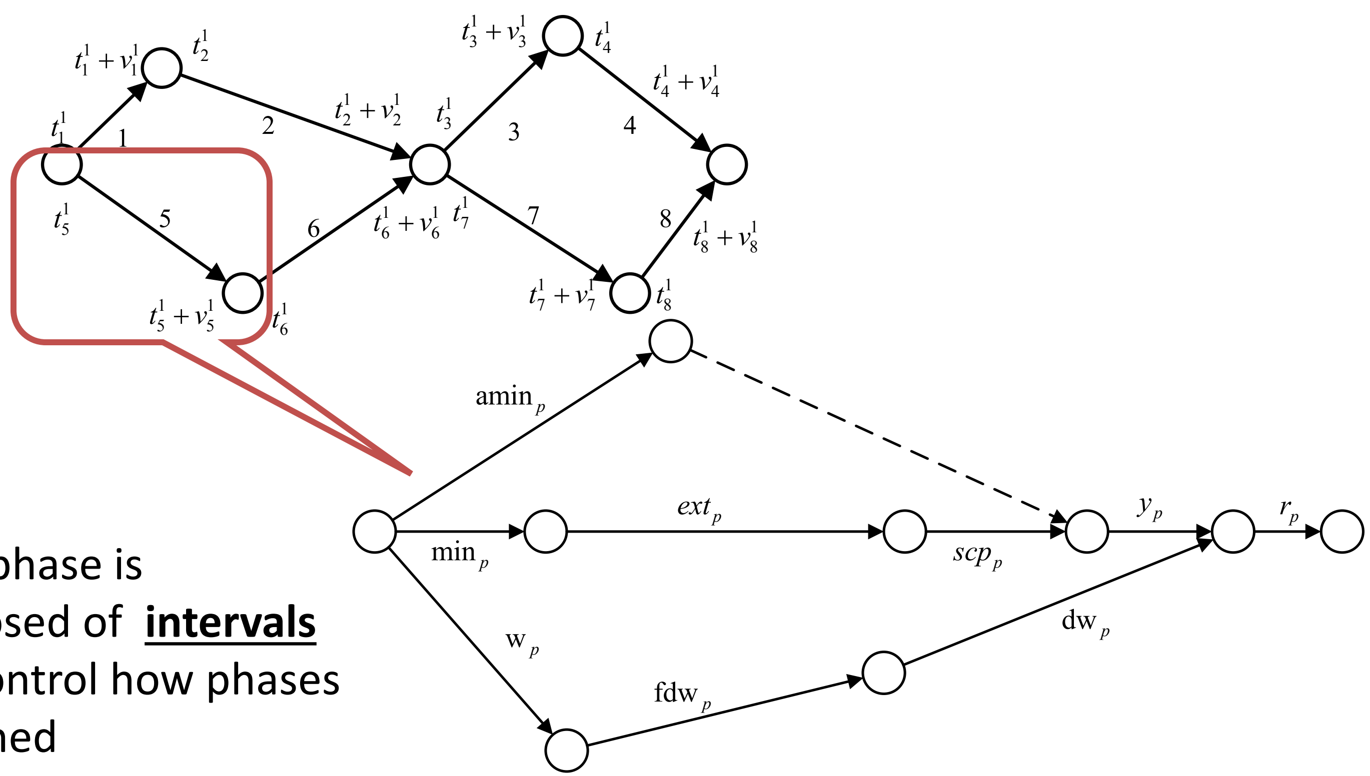
Dual Ring Controller (Core Logic)



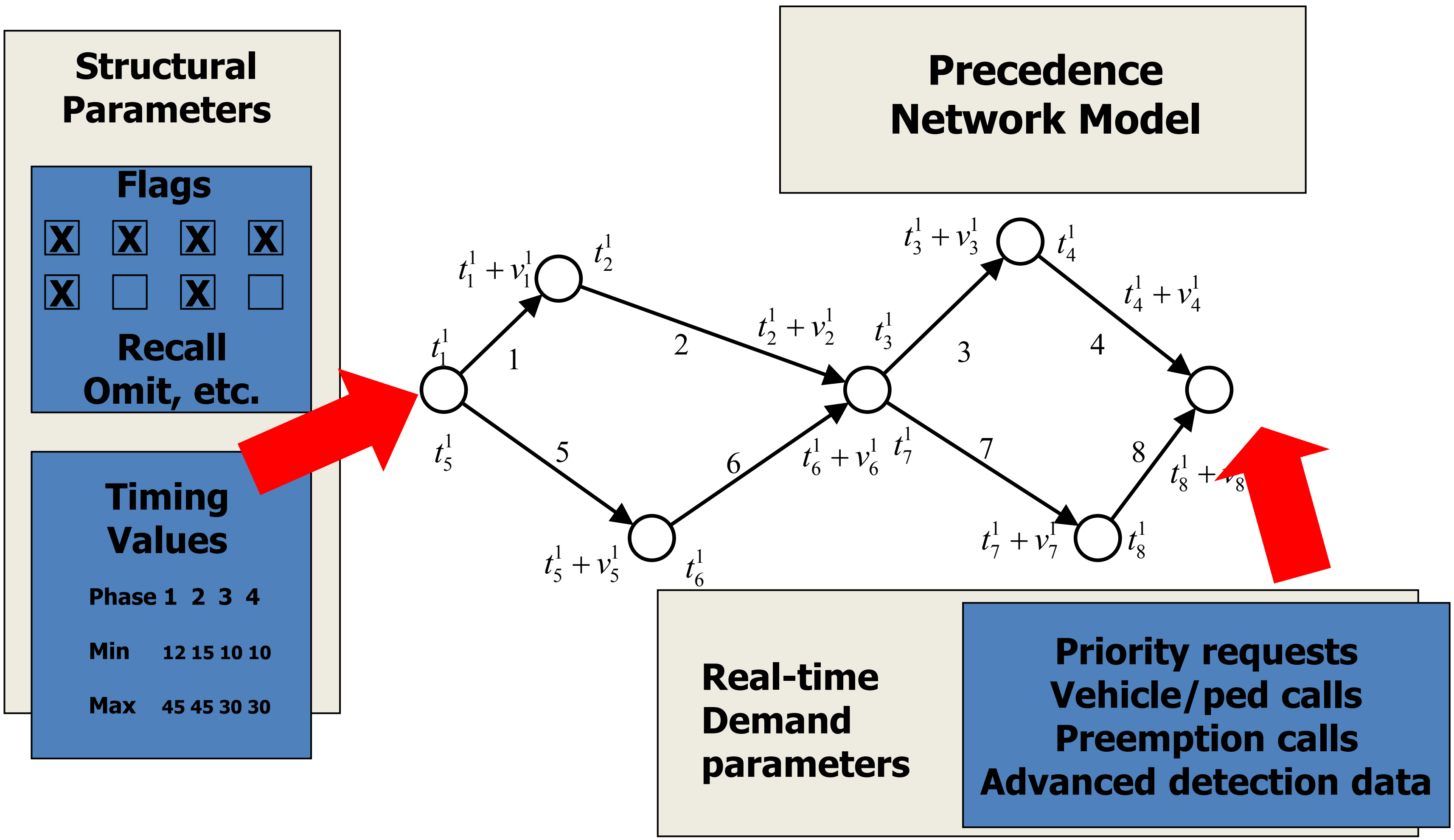

Precedence Diagram (works for general precedence relationships – not just dual ring)

# Phase Logic




Every phase is composed of **intervals** that control how phases are timed

# Phase Configuration and Real-time Data

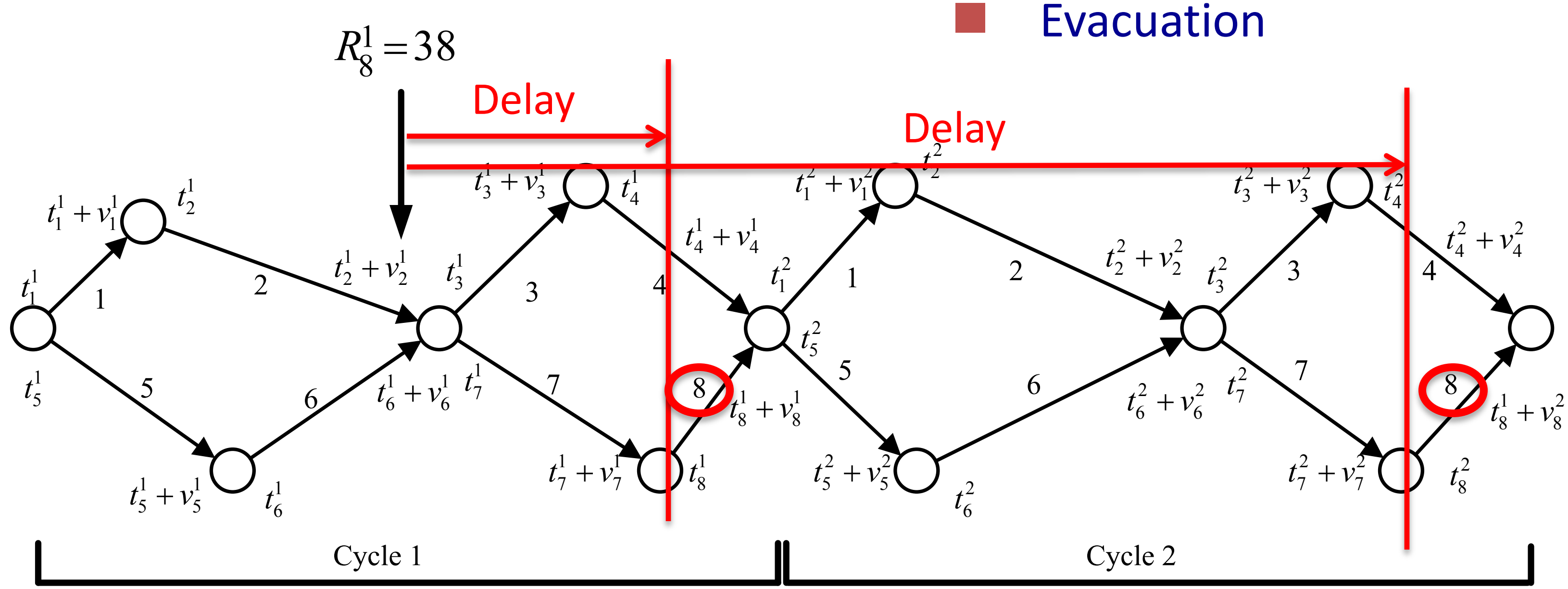


# Requests for Priority

- Preemption
  - Heavy Rail
  - Emergency Vehicles*

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

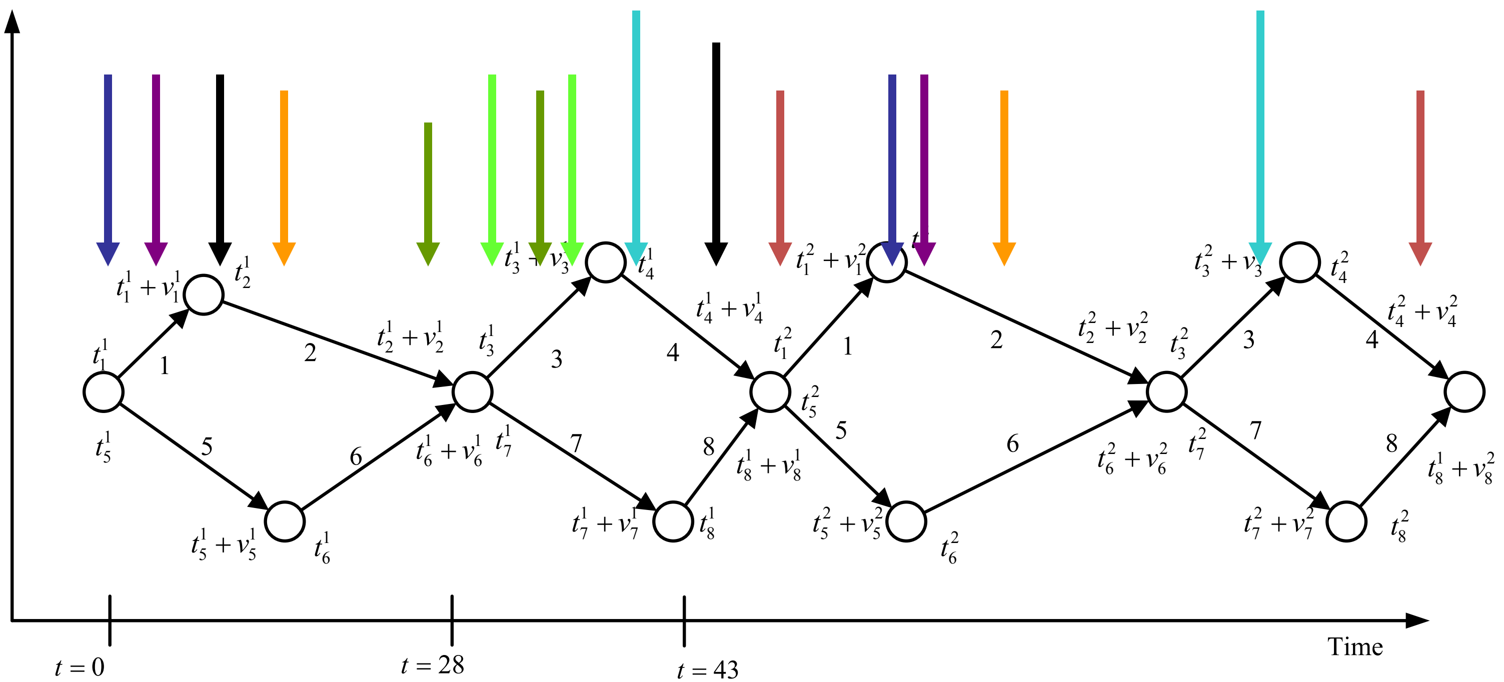
Request for
Phase 8 at t=38



# Multiple Requests for Priority

*There could be many requests from many vehicles*

- Phase 1
- Phase 2
- Phase 3
- Phase 4
- Phase 5
- Phase 6
- Phase 7
- Phase 8



# Model Formulation

$$\begin{aligned}&\textit{Minimize} \quad \text{Total Priority Delay} + \text{Vehicle Cost}\\ &\textit{s.t.}\end{aligned}$$

Precedence Constraints

Phase Duration & Interval Constraints

Service Phase Selection Constraints

Phase Calls and Flags

Decision Variables:

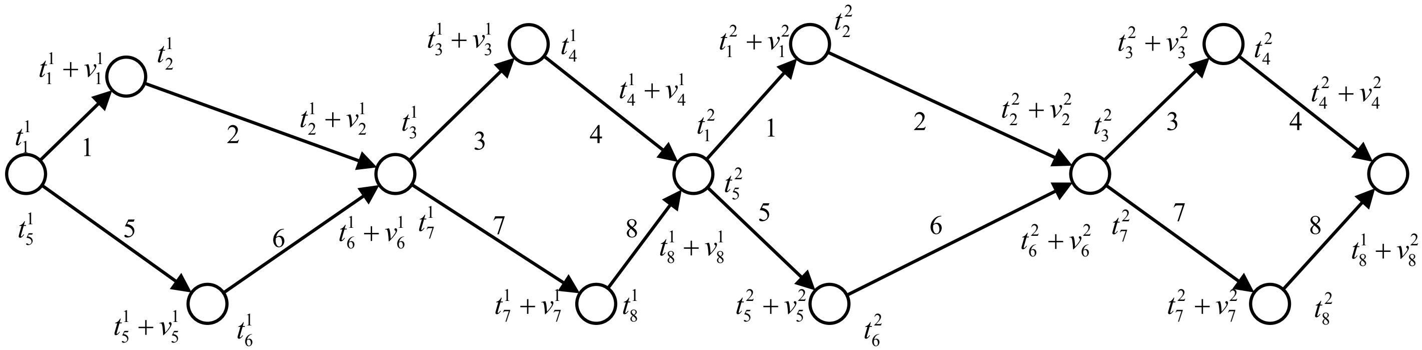
phase start times = $t_p^j$, durations = $v_p^j$

green time = $g_p^k$, given yellow = $y_p$, red = $r_p$

$$v_p^k = \begin{cases} g_p^k + y_p + r_p & \textit{if } g_p^k > 0 \\ 0 & \textit{if } g_p^k = 0 \end{cases}$$

service phase = $\theta_{\mathrm{e}}^{\mathrm{j}}, \theta_{\mathrm{s}}^{j} \in \{0,1\}$ , phase and interval skipping = $\overrightarrow{S\underline{\quad}_p^j} \in \{0,1\}$

# Precedence Constraints




$$
\begin{aligned}
&t_1^1 = 0 \\
&t_5^1 = 0 \\
&t_2^k = t_1^k + v_1^k \\
&t_6^k = t_5^k + v_5^k \\
&t_3^k = t_2^k + v_2^k, \quad t_3^k = t_6^k + v_6^k \\
&t_7^k = t_2^k + v_2^k, \quad t_7^k = t_6^k + v_6^k \\
&t_4^k = t_3^k + v_3^k \\
&t_8^k = t_7^k + v_7^k \qquad\qquad \text{for} \quad k = 1, \ldots, K \\
&t_1^{k+1} = t_4^k + v_4^k, \quad t_1^k = t_8^k + v_8^k \\
&t_5^{k+1} = t_4^k + v_4^k, \quad t_5^k = t_8^k + v_8^k \qquad \text{for} \quad k = 1, \ldots, K-1
\end{aligned}
$$

# Phase Duration Constraints

$$t_p^k \geq 0,$$

$$\underline{g_p^k}(\Omega, \Phi, \omega, s_p^k) \leq g_p^k \leq \overline{g_p^k}(\Omega, \Phi, \omega, s_p^k), \quad \text{for all } p \text{ and } k$$

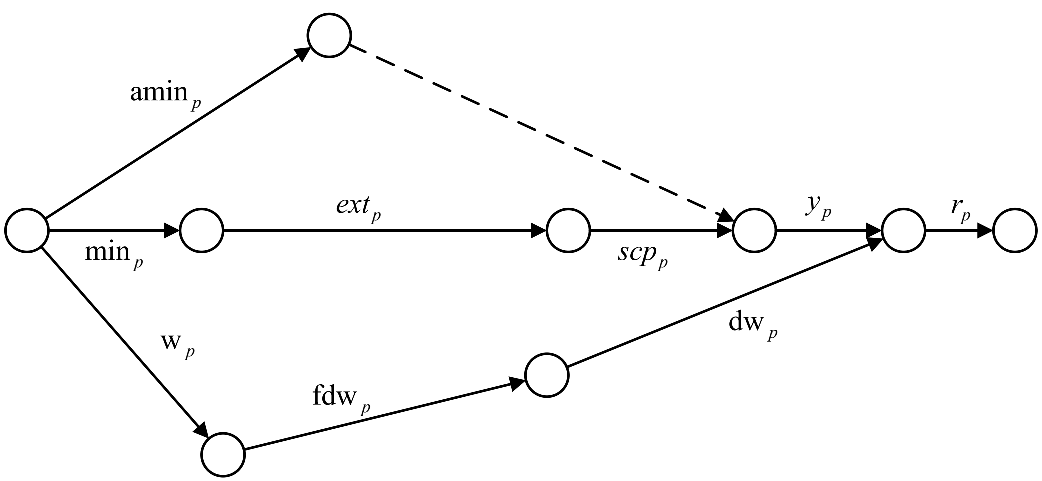
where,

$\Omega$ 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
$s_p^k$ are binary interval decision variables (skip, don't skip)

# Phase Interval Constraints

$$\underline{g_p} = Max\begin{Bmatrix} D\min_p \bullet (1 - X\min \mathrm{R}_p), \\ Damin_p \bullet Cphs_p (1 - Sa\min^k{}_p), \\ (Dw_p + Dfdw_p) \bullet Cped_p \bullet (1 - Sped_p^k), \\ D\max_p \bullet X\max R_p \end{Bmatrix} \bullet (1 - SC_p^k) \bullet (1 - Xomit_p)$$

$$\overline{g_p} = \left\{\max\left(D\max_p, (Dw_p + Dfdw_p) \bullet Cped_p\right)\right\} \bullet (1 - SC_p^k) \bullet (1 - Xomit_p)$$




Notation

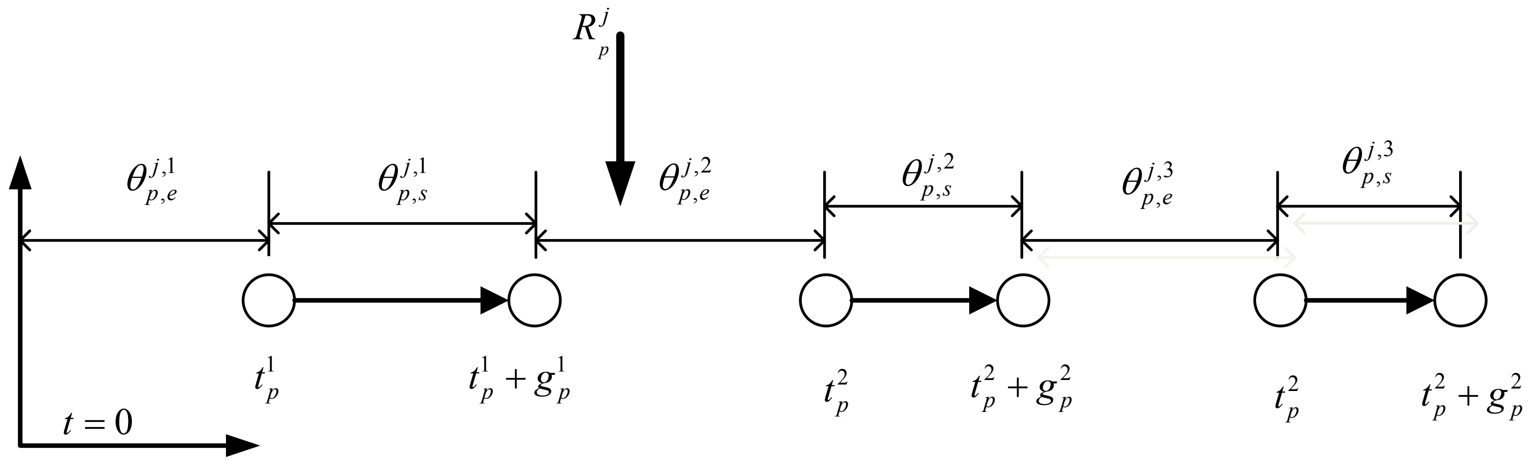
$D\_\_\_$ = Phase Parameters ($\Omega$)

$X\_\_\_$ = Phase Flags ($\Phi$)

$C\_\_\_$ = Phase Calls ($\omega$)

$S\_\_\_^k_p$ = Phase Skip Decision Variable

# Service Phase Selection Constraints




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

$\theta_{p,s}^{j,k} \in \{0,1\}$ 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 $R_p^j$

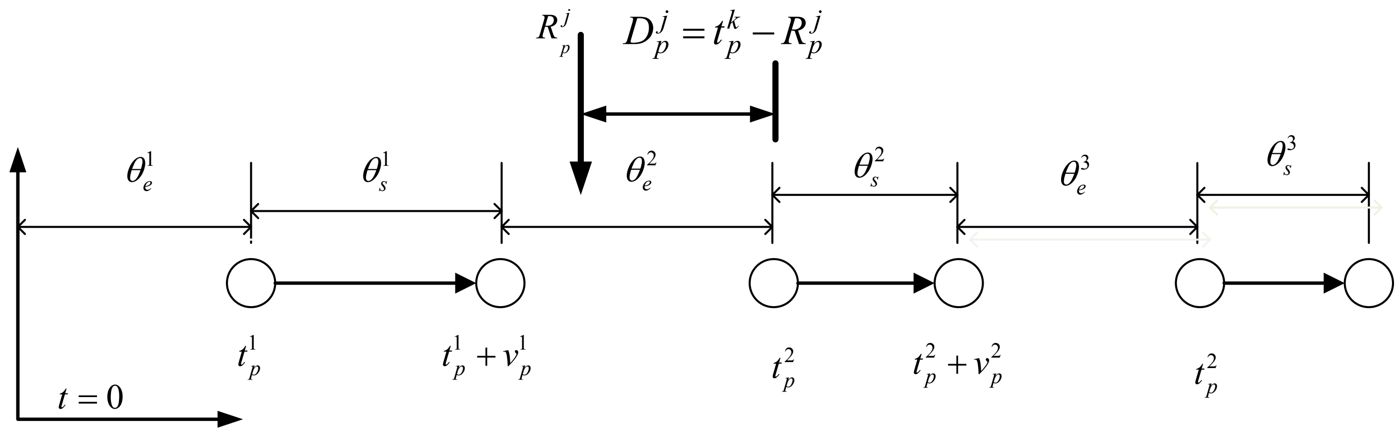
# Service Phase Selection Constraints

$$
\begin{aligned}
t_p^1 - R_p^j &\geq (\theta_{p,e}^{j,1} - 1)M \\
t_p^1 + v_p^1 - R_p^j &\geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} - 1)M \\
t_p^2 - R_p^j &\geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2} - 1)M \\
t_p^2 + v_p^2 - R_p^j &\geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,2} - 1)M \\
t_p^3 - R_p^j &\geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,3} - 1)M \\
t_p^3 + v_p^3 - R_p^j &\geq (\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,3} + \theta_{p,s}^{j,3} - 1)M
\end{aligned}
$$

$$
\begin{aligned}
R_p^j - t_p^1 &\geq -\theta_{p,e}^{j,1} M \\
R_p^j - (t_p^1 + v_p^1) &\geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1})M \\
R_p^j - t_p^2 &\geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2})M \\
R_p^j - (t_p^2 + v_p^2) &\geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,2})M \\
R_p^j - t_p^3 &\geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,3})M \\
R_p^j - (t_p^3 + v_p^3) &\geq -(\theta_{p,e}^{j,1} + \theta_{p,s}^{j,1} + \theta_{p,e}^{j,2} + \theta_{p,s}^{j,2} + \theta_{p,e}^{j,3} + \theta_{p,s}^{j,3})M
\end{aligned}
$$

# Total Priority Delay

$$Minimize \quad D = \sum_{(p,j)} \sum_{k} \theta_{p,e}^{j,k} (t_p^k - R_p^j)$$



# 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 $\sum_{j,p,k} D_{jpk}$

Data: $R_{jp}$ $g_{pk}^{\min}$ $g_{pk}^{\max}$

Variable: $D_{jpk}$ $t_{pk}$ $g_{pk}$ $\theta_{jpk}$

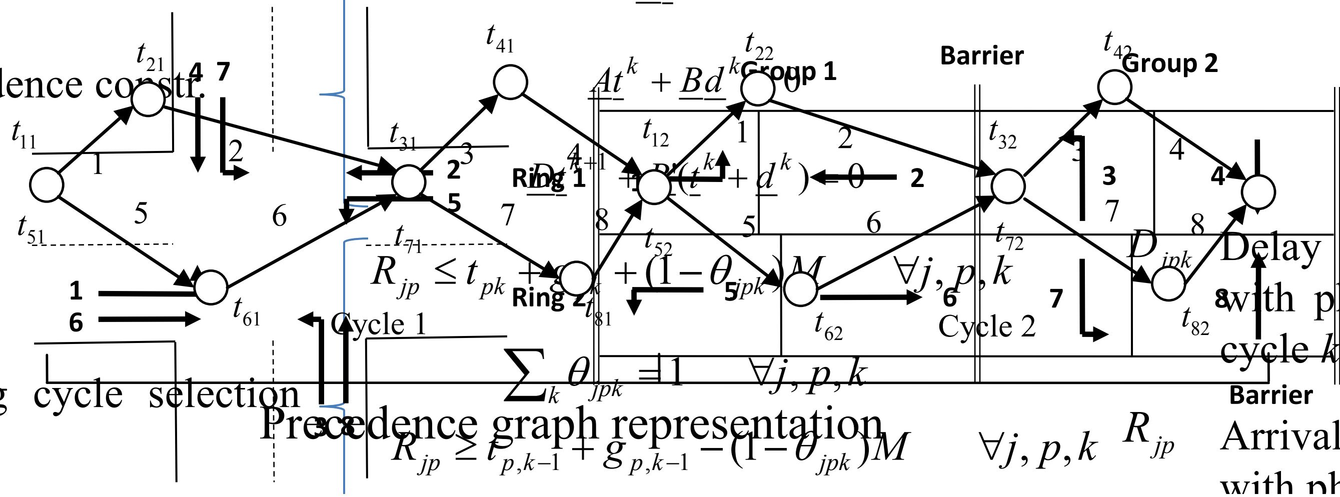
Subject to

Precedence constr.

$$\underline{E}\underline{t}^1 = 0$$

$$\underline{A}\underline{t}^k + \underline{B}\underline{d}^k \ge 0$$

$$\underline{D}\underline{t}^{k+1} + \underline{D}'(\underline{t}^k + \underline{d}^k) = 0$$




Precedence graph representation

Dual-ring, eight-phase controller

$$R_{jp} \le t_{pk} + g_{pk} + (1-\theta_{jpk})M \quad \forall j,p,k$$

$D_{jpk}$ Delay for $j$th request with phase $p$, served in cycle $k$.

Serving cycle selection constr.

$$\sum_k \theta_{jpk} = 1 \quad \forall j,p,k$$

$$R_{jp} \ge t_{p,k-1} + g_{p,k-1} - (1-\theta_{jpk})M \quad \forall j,p,k$$

$R_{jp}$ Arrival time for $j$th request with phase $p$.

$\theta_{jpk}$ ... request with phase $p$ is served in cycle $k$.

Delay evaluation constr.

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

$$D_{jpk} \ge 0 \quad \forall j,p,k$$

Phase duration constr.

$$g_{pk}^{\min} \le g_{pk} \le g_{pk}^{\max} \quad \forall p,k$$

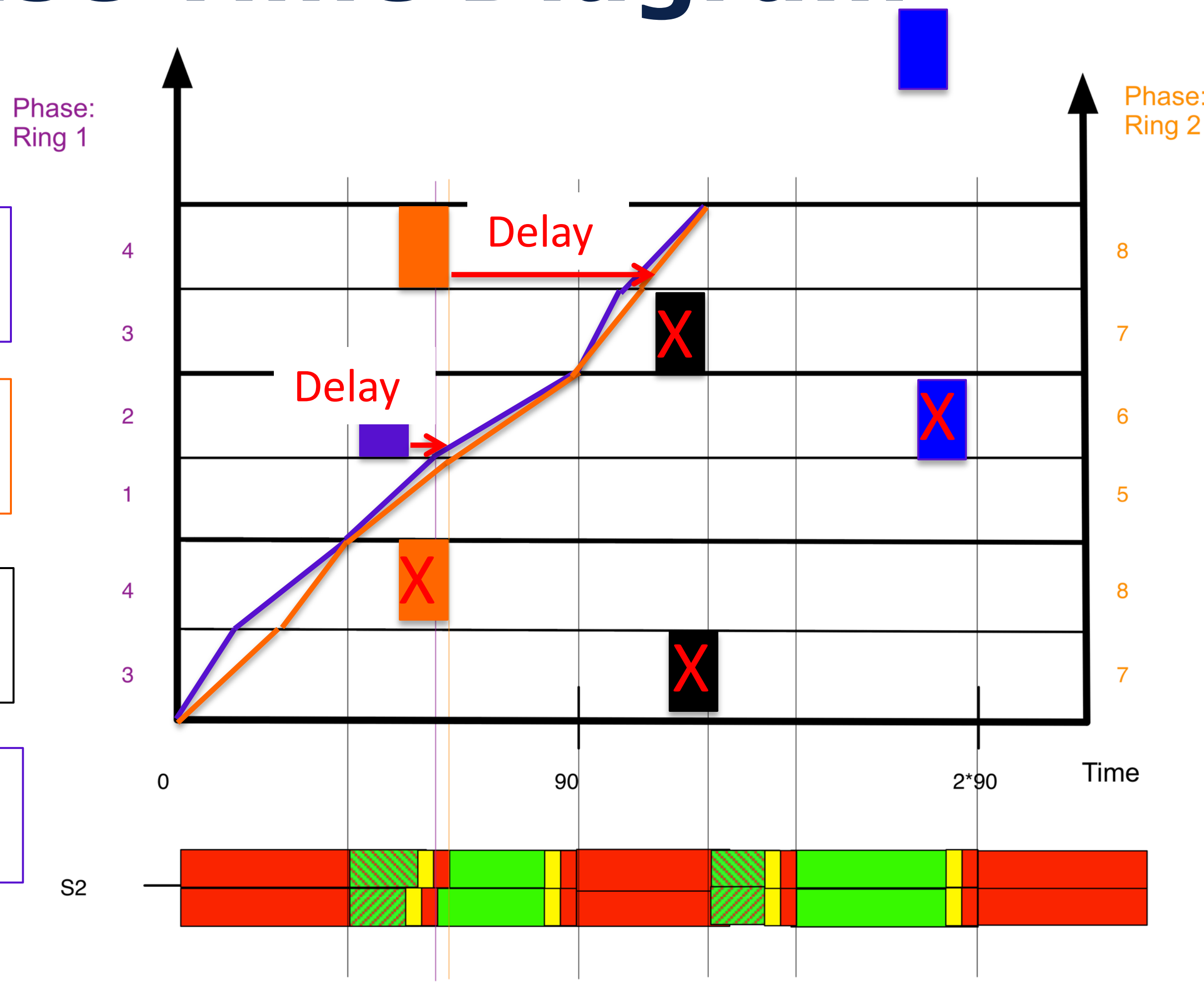
# Serving Priority Requests – Phase Time Diagram

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



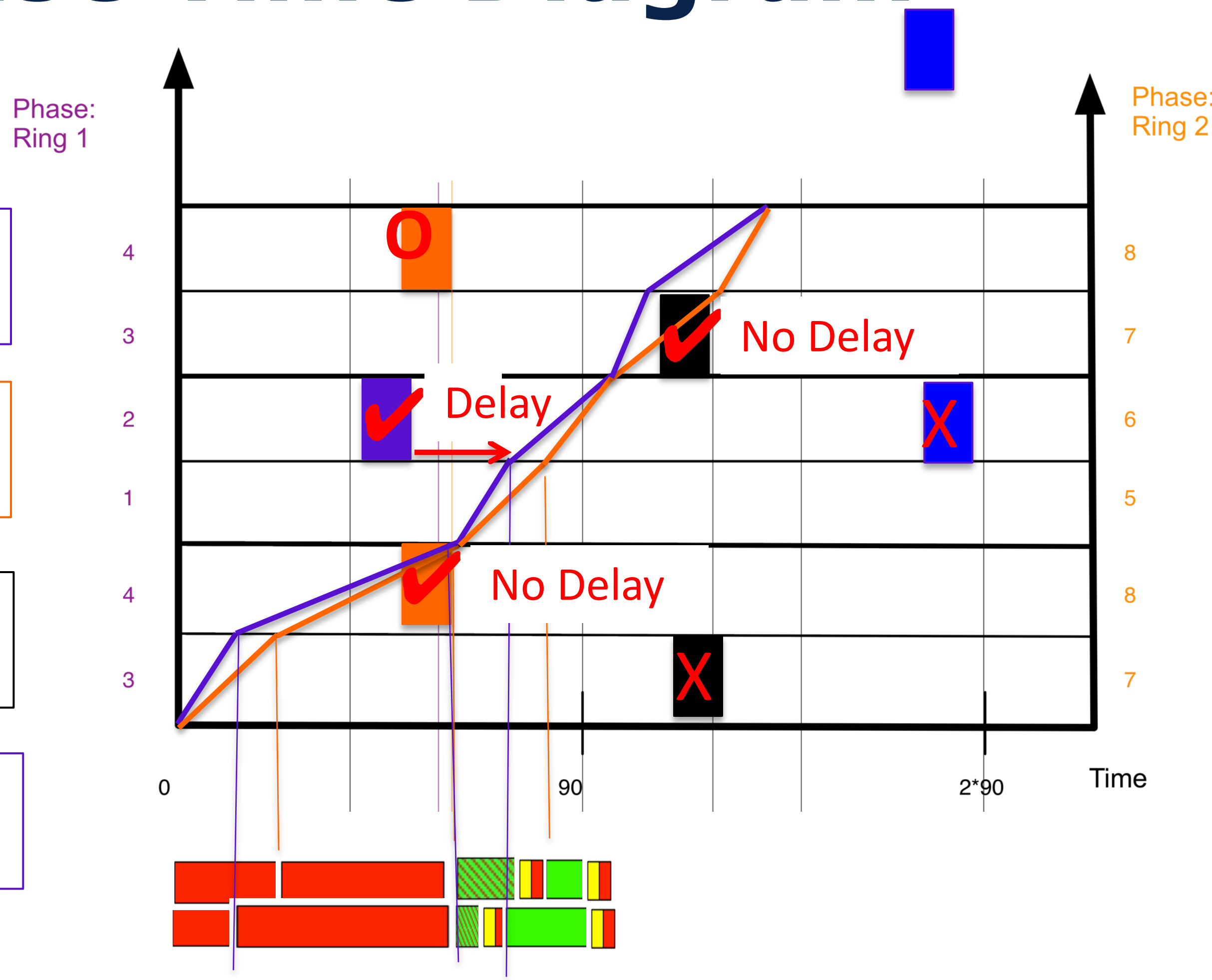
# Serving Priority Requests – Phase Time Diagram

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

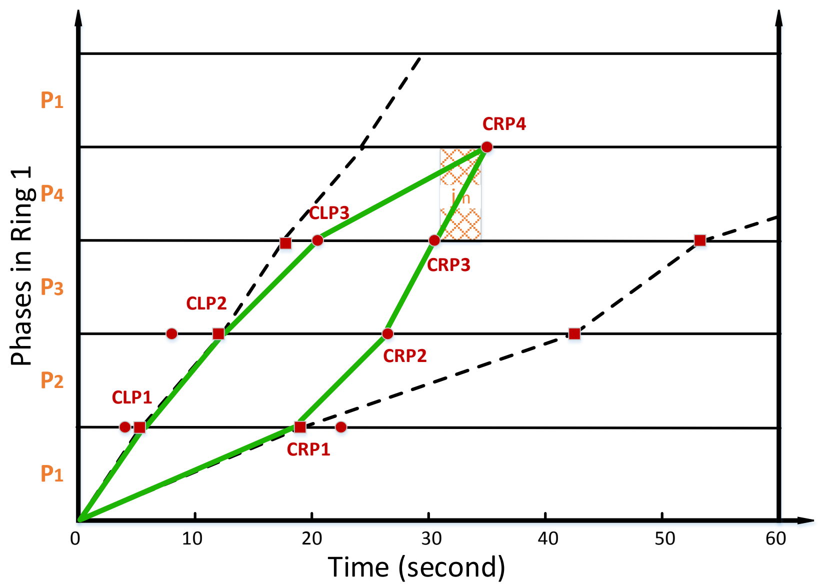


# Flexible Implementation Algorithm (Zamanipour et al., 2016)

- Critical points for one request

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

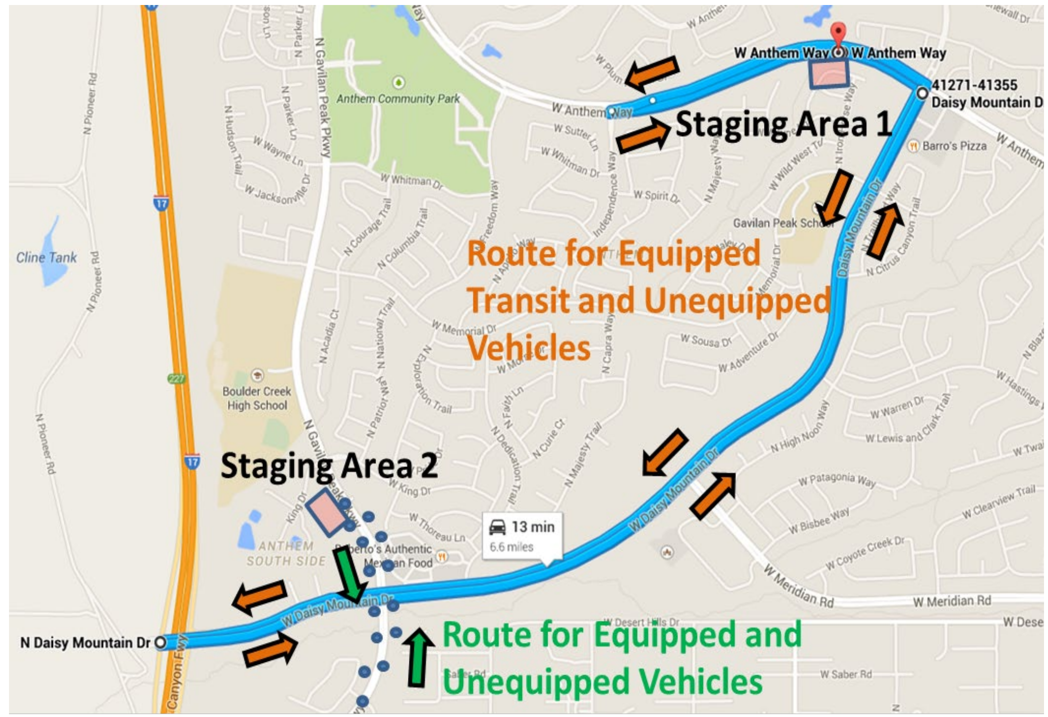
**CRP1:** min {FR1, BR4}
**CRP2:** min {FR2, BR3}
**CRP3:** min {FR3, BR2}
**CRP4:** BR1




< 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



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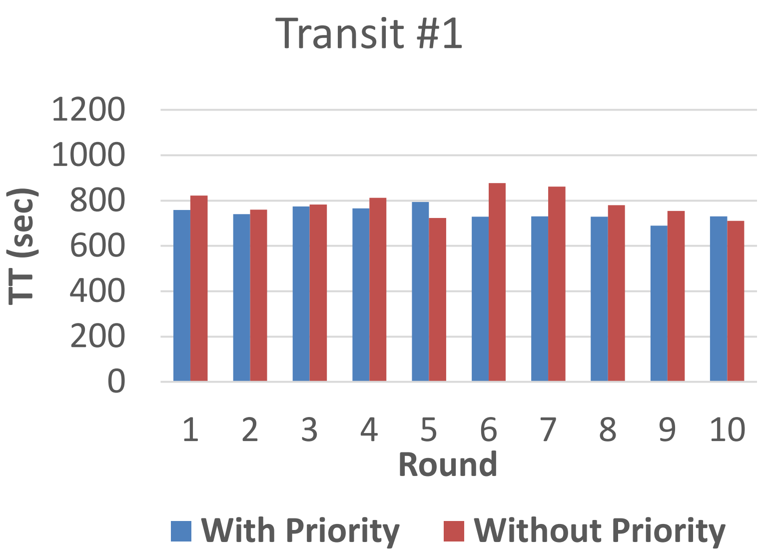
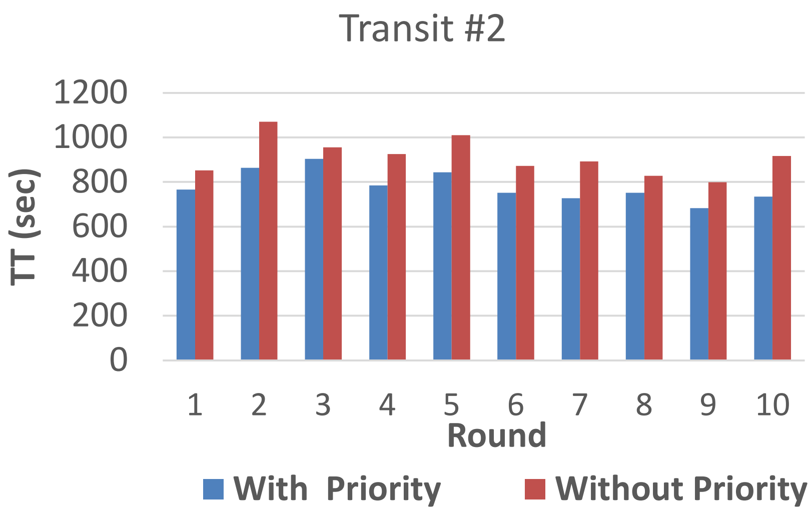
# Field Test Result for Transit Priority




| | Baseline (2 buses without Priority Requests for 10 Round Trips) | TSP (2 buses with Priority Requests for 10 Round Trips) | Improvement (%) |
|---|---|---|---|
| **Average TT (sec)** | 850.12 | 762.56 | **-10.3** |
| **TT Standard Deviation** | 91.13 | 53.48 | **-41.3** |

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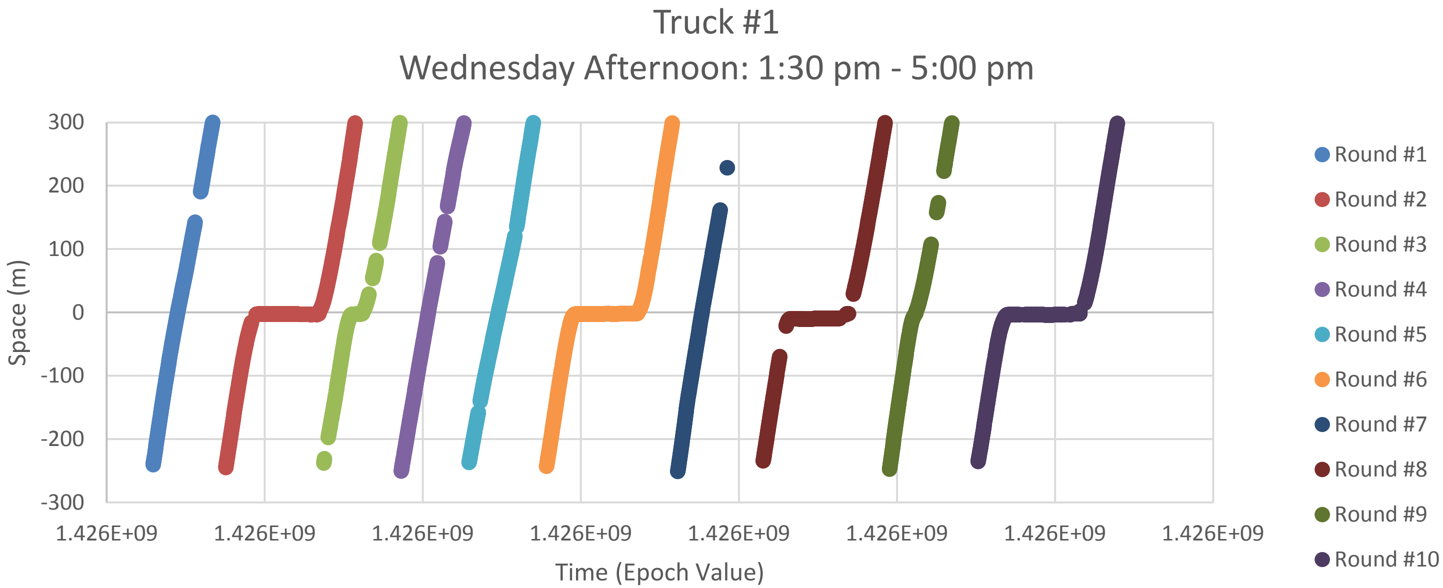
# Time-Space Diagram without MMITSS

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

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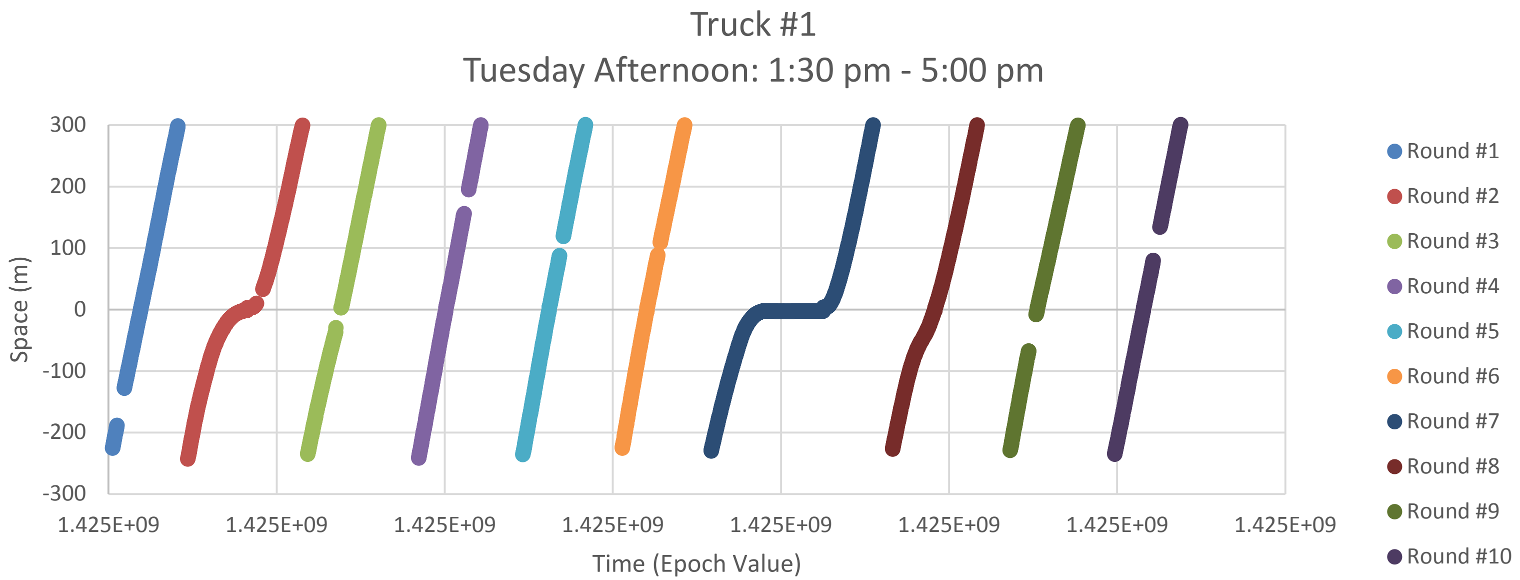
# Time-Space Diagram with MMITSS

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

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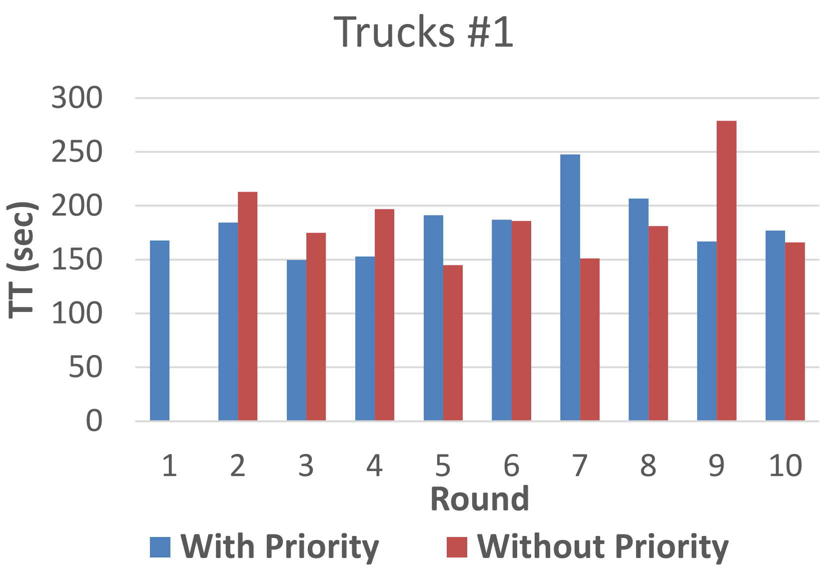
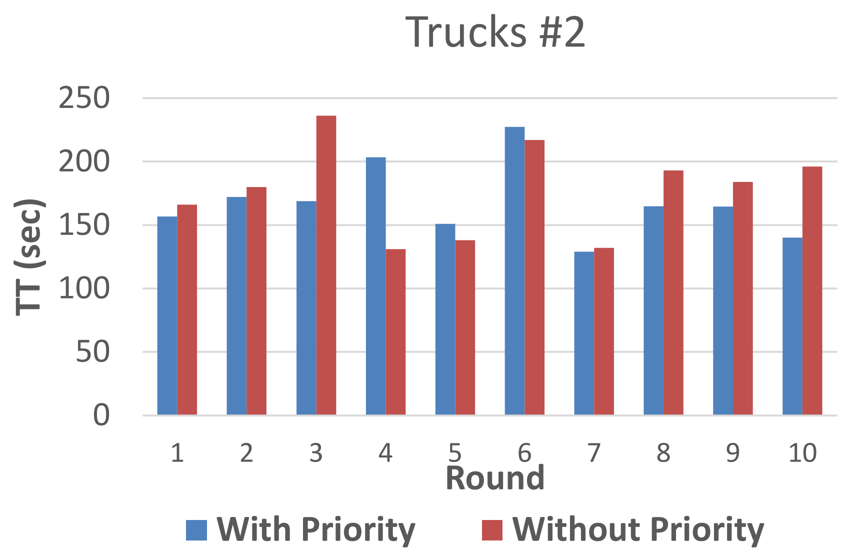
# Findings for Freight Priority

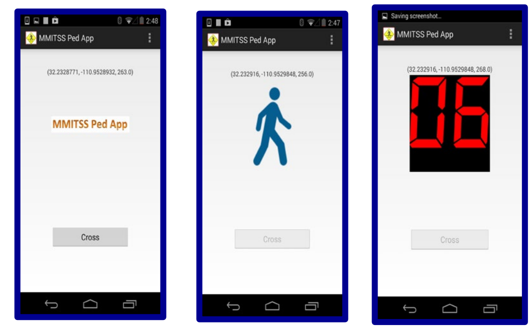



| | Baseline (2 trucks without Priority for 10 Round Trips) | FSP (2 trucks with Priority for 10 Round Trips) | Improvement (%) |
|---|---|---|---|
| **Average TT (sec)** | 182.42 | 175.44 | **-3.84** |
| **TT Standard Deviation** | 36.28 | 28.37 | **-21.78** |

# MMITSS Pedestrian Smartphone App


MMITSS Pedestrian Smartphone app




Allows Pedestrian to receive auditory and haptic feedback

- Align with Crosswalk
- Send Call for Service
- Be given WALK
- PedCLEAR Countdown

Sara Khosravi, PhD Student

Savari SmartCross (SBIR) Application Architecture

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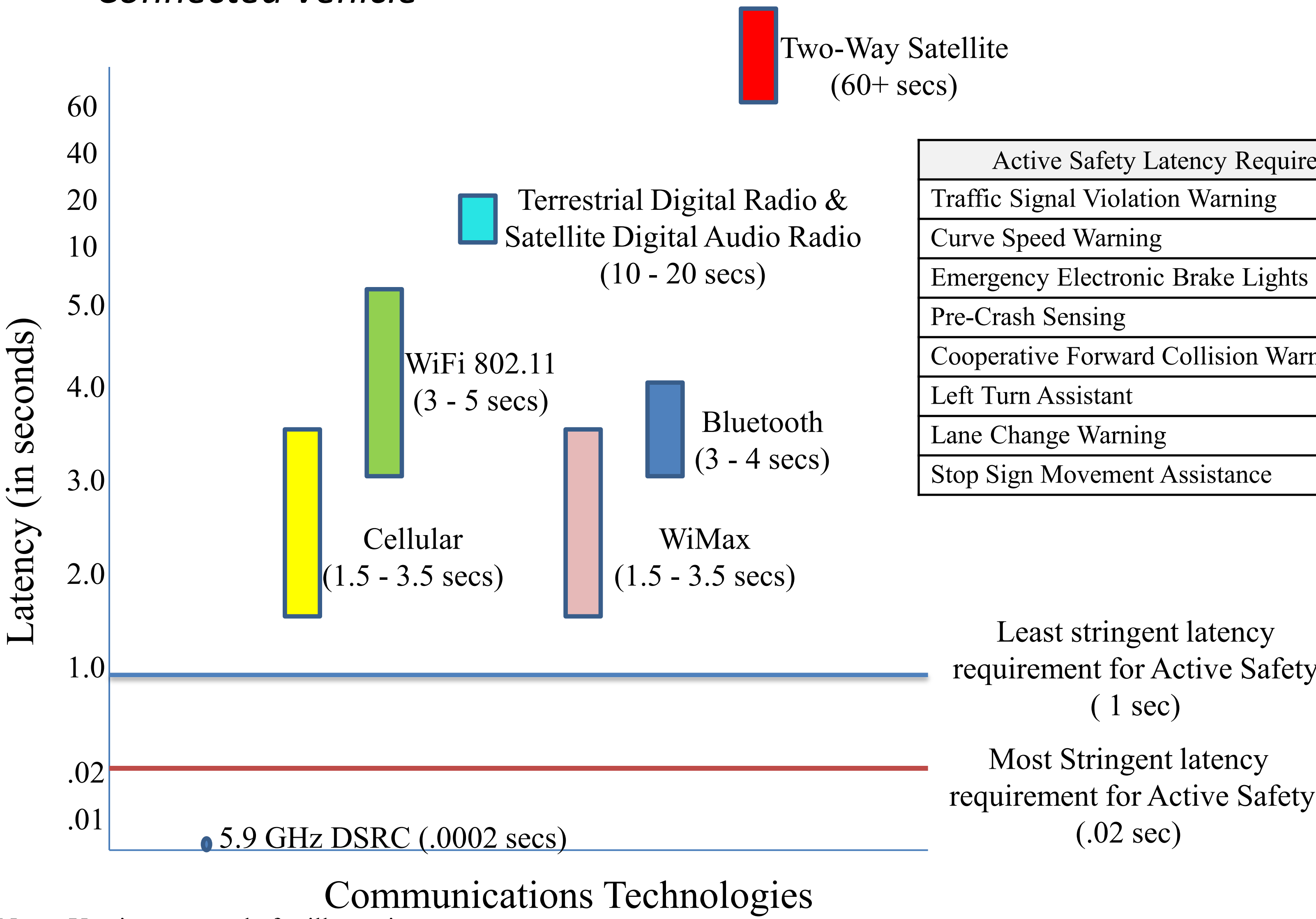
# Latency vs. Communications Technologies For IntelliDrive[SM]

*From US DOT Briefings on Connected Vehicle*



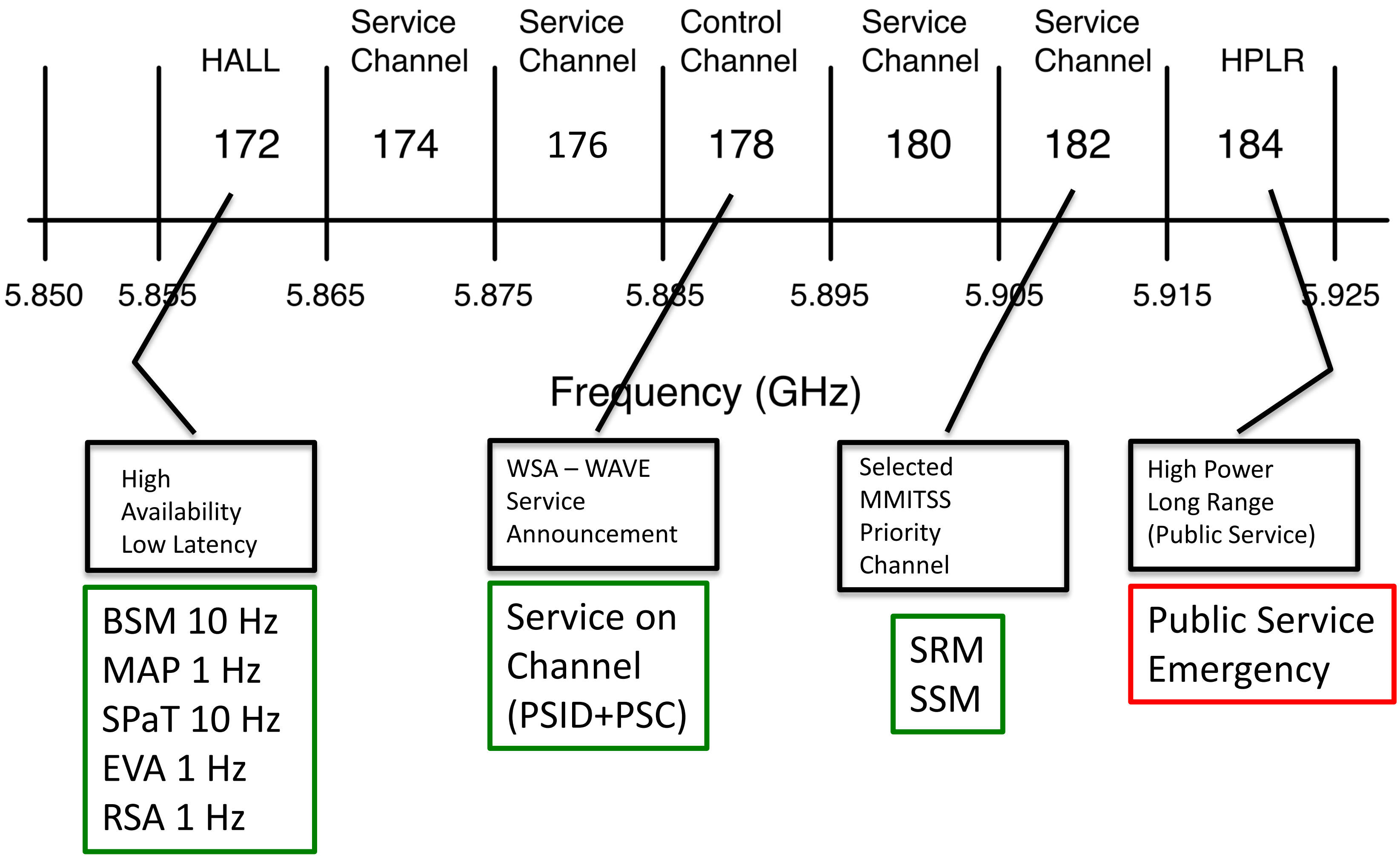

| Active Safety Latency Requirements (secs) | |
|---|---|
| Traffic Signal Violation Warning | 0.1 |
| Curve Speed Warning | 1.0 |
| Emergency Electronic Brake Lights | 0.1 |
| Pre-Crash Sensing | 0.02 |
| Cooperative Forward Collision Warning | 0.1 |
| Left Turn Assistant | 0.1 |
| Lane Change Warning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

Note: Y-axis not to scale for illustration purposes



Data source: Vehicle Safety Communications Project – Final Report

# WAVE Communications




Source: Delgrossi, L. and T. Zhang, Vehicle Safety Communications: Protocols, Security, and Privacy, Wiley, 2012.