Maricopa County Arizona
Connected Vehicle Testbed

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Intelligent Transportation Systems – Wisconsin
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Connected Vehicles ...

5.9 GHz DSRC vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communications

SAE J2735 Message Set: BSM, SPAT, MAP, SRM, SSM, RSA...

Applications:
SAFETY
MOBILITY
ENVIRONMENT
Basic Building Blocks

- Basic Safety Message (BSM) (10 Hz)
- Signal Phase and Timing Data (SPaT) (10 Hz)
- MAP Data (1 Hz)
- Digital Description of Roadway (D. Kelley, 2012)

All message transmission is broadcast

WAVE Message (IEEE 1609)
National Affiliated CV Test Beds
Maricopa County DOT SMARTDrive Program

• Several successful demos during last 3 years:
  • Inaugural SMARTDrive, April 26, 2012
  • AASHTO SCOR, December 3, 2013
  • APTA, March 20, 2014
  • FHWA Scanning Tour, July 22, 2014
  • TRB Sig. Com., May 19, 2015
Test Bed Traffic Info

10 ASDs in:
- Valley Metro Bus
- Daisy Mountain Fire
- MC DOT REACT Vehicles
- Passenger Cars

Traffic Demand

DaisyGavilan_SB Left Lane_Det #2
Multi-Modal Intelligent Traffic Signal Systems
MMITSS

• Technical
  • University of Arizona (Prime)
  • University of California Berkeley (PATH)
  • Savari
  • Econolite

• Sponsors - Pooled Fund Project
  • FHWA
  • Virginia DOT/UVA
  • Maricopa County DOT
  • Caltrans
  • Minnesota DOT
  • Florida DOT
  • Michigan DOT
  • ...
4 Major Components in MMITSS

- Intelligent Traffic Signal Control
- Traffic Signal Priority
- Pedestrian Assistance Application
- Real-Time Performance Observation
MMITSS Basic Concept

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

Section 1
- Priority for
  - Trucks

Section 2
- Priority for
  - Transit
  - Pedestrians

Real-Time Performance Observation
- Travel Time (by mode and movement)
- Delay (by mode and movement)
- Throughput (by mode and movement)
- Stops (by mode and movement)
MMITSS Architecture
Signal Control with Connected Vehicles

Wifi? Bluetooth?
3G, 4G LTE

DSRC 5.9GHz?
Messages (SAE J2735)

• Basic Safety Message (BSM)
  • Part I: temp id, location (GPS), speed, heading, steering angle, brakes, size
  • Part II: Safety extensions (path history, prediction, GPS correction), Vehicle status (wipers, lights, brakes, sensors, throttle, size, …)

• MAP (Geometric Description)
• SPaT (Signal Phase and Timing)
• Signal Request Message (SRM)
  • Request (preempt or priority id), inLane, outLane, vehicle type), time of service, end of service, transit status (ada, bike, occupancy, door), vehicle ID, BSM data, vehicle status (EV lights)

• Signal Status Message (SSM)
  • Signal status (preempt, priority, transition, flash), preempt or priority cause (vehicle)

• Priority Status Message (PSM – being proposed)
  • NTCIP 1211 Signal Request Table
    • Contains a table of all Active Requests received by the infrastructure Priority Request Server from Vehicles
Trajectory Awareness of Connected Vehicles

• Store vehicle trajectories
  - BSM: position (GPS, local), speed, heading
  - Frequency: 0.5s
• Construct MAP
• Locate vehicle on MAP: calculate vehicle states, phase, ETA
• Arrival Table: Input for phase allocation algorithm
• Reflect reality
  - Ensure vehicle privacy
  - Geo-fencing
Intelligent Phase Allocation

- Provide signal control for regular vehicles: Structure
- Extension of optimization of phases (COP) algorithm
  - Arrival data from CV as the input
  - Two-level optimization (Dynamic Programming)

- Two control objectives: minimizing total delay, minimizing queue length
Intelligent Phase Allocation (Cont.)

• Market penetration rate of connected vehicles (Goodall, 2013)
• Estimation of vehicle location and speed (EVLS) of unequipped vehicles

Add detector data under low penetration rate case
Signal Priority Control

Priority control algorithm includes:

- A mixed integer linear programming (MILP) mode
  - Dual ring barrier signal controller logic
  - Precedence Diagram
- A signal implementation algorithm
  - Time-Phase Diagram
Signal Priority Request

- Priority vehicle broadcasts signal request message (SRM) that contains requested phase and estimated time of arrival (ETA)

- Different travel modes have their own specific characteristics that affect ETA

- Analyzing the DSRC range (300m)
Mathematical Formulation

\[
\min_{i, g, \theta, \mu} \quad \alpha \left( \sum_{m, j} w^m d_{jm} \right) + \beta \left( \sum_{p, k} c_{d_{p,k}} \right) + \gamma \left( \frac{\sum_{p, i} N_{i, rd_{i,p(i)}}}{\sum_{i} N_i} \right)
\]

\[
\alpha, \beta, \gamma \quad \text{are the weights assigned to priority vehicles, coordination, and regular vehicle}
\]

\[
 w^m \quad \text{is the weight assigned to mode } m
\]

\[
 d_{jm} \quad \text{is the delay of } j^{th} \text{ request from mode } m
\]

\[
 c_{d_{p,k}} \quad \text{is coordination delay for coordinated phase } p \text{ in cycle } k
\]

\[
 rd_{i,p(i)} \quad \text{is the regular vehicle delay for the vehicle that arrives at time } i \text{ for phase } p
\]

\[
 t^k \quad \text{is starting time of phase } p \text{ in cycle } k
\]

\[
 g^k \quad \text{is green time of } p \text{ in cycle } k
\]

\[
 \theta^m_{j,p} \in \{0,1\} \quad \text{whether request } j \text{ of mode } m \text{ is served in cycle } k \text{ or not}
\]
Pedestrian Crossing

- The TRB Traffic Signal System Committee
- TRB Accessibility Committee
- TRB Pedestrian Committees
- SAAVI (Southern Arizona Association for the Visually Impaired)
- Selected group
Performance Observation and Monitoring

• Collect Basic Safety Message Data
  ✓ Detailed Spatial and Temporal information
  ✓ High resolution vehicle Trajectories
  ✓ By mode, by movement analysis

• Process Trajectories to compute observed

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Abbreviation</th>
<th>Unit</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time</td>
<td>TT</td>
<td>Second</td>
<td>MRP_EquippedVehicleTrajectoryAware</td>
</tr>
<tr>
<td>Delay</td>
<td>D</td>
<td>Second</td>
<td>MRP_EquippedVehicleTrajectoryAware</td>
</tr>
<tr>
<td>Travel Time Variability</td>
<td>TTV</td>
<td>Second</td>
<td>MRP_EquippedVehicleTrajectoryAware</td>
</tr>
<tr>
<td>Delay Variability</td>
<td>DV</td>
<td>Second</td>
<td>MRP_EquippedVehicleTrajectoryAware</td>
</tr>
<tr>
<td>Queue Length</td>
<td>QL</td>
<td>Meter/number of vehicles</td>
<td>MRP_EquippedVehicleTrajectoryAware</td>
</tr>
<tr>
<td>Number of Stops</td>
<td>NS</td>
<td></td>
<td>MRP_EquippedVehicleTrajectoryAware</td>
</tr>
<tr>
<td>Volume</td>
<td>V</td>
<td></td>
<td>MRP_TrafficControllerInterface</td>
</tr>
<tr>
<td>Occupancy</td>
<td>O</td>
<td>%</td>
<td>MRP_TrafficControllerInterface</td>
</tr>
<tr>
<td>Market Penetration Rate</td>
<td>MPR</td>
<td>%</td>
<td>MRP_EquippedVehicleTrajectoryAware &amp; MRP_TrafficControllerInterface</td>
</tr>
</tbody>
</table>

• Performance Measures Used for
  • Monitoring and Assessment
  • Section Level Control
Partial Trajectories to Preserve the Privacy

Probability of changing ID = \( p = \frac{\text{Travel Time of vehicle}_j}{300} \)

\[
ETT = \left[ \sum_{i=1}^{n} \frac{TT_i}{D_i} + \sum_{j=1}^{m_1} \frac{TT_{1j}}{D_{1j}} + \sum_{j=1}^{m_2} \frac{TT_{2j}}{D_{2j}} \right] \times \left[ \sum_{i=1}^{n} D_i + \sum_{j=1}^{m_1} D_{1j} + \sum_{j=1}^{m_2} D_{2j} \right] / [n + m_1 + m_2]
\]
Simulated Travel Time Estimation

- Daisy Mountain and Memorial Drive
- Travel Time Data accumulated every 5 Minutes for Northbound Through Movement
Research and Development Steps

• Algorithm concept definition and application development

• Simulation testing on calibrated models in lab environment
  ✓ Traffic Signal Data
  ✓ Traffic Demand and Input
  ✓ DSRC Range

• Field testing at the intersection of Mountain and Speedway in Tucson, AZ

• Arizona Connected Vehicle Test Bed implementation
VISSIM Simulation Environment

Arizona CV Test Bed

• Hardware-in-the-loop Simulation (HILS)
• Software-in-the-loop Simulation (SILS)
• Drivermodel.dll API
  ✓ Coordinates transformation: local -> GPS (Farrell and Barth, 1999)
  ✓ Pack J2735 BSM/SRM messages (ASN1 encoder/decoder)
  ✓ Send through UDP socket
• GPS Error Modeling
• OBE Message Distributor
• Docker
Simulation Platform Architecture

SIL/CID

VISSIM

driverModel.dll

VISSIM x-y plane to GPS (WGS - 84)
Vehicle Position Mapping

Signal Controller

Ethernet - NTCIP 1202

In-Vehicle Display (HIL)

Ethernet or DSRC (5.9 GHz)
[SAE J2735]

MIMITERSS

RSE

OBE

OBE

OBE #m

OBE Distributor

RSE

RSE

GID

GID

GID

VISSIM
GPS Error Modeling

• GPS Error in real world, but doesn’t exist in simulation
• Data collection: 2 hours of 1Hz GPS data

• Univariate Autoregressive Integrated Moving Average (ARIMA)
  • \( x_t = \phi_1 x_{t-1} + \phi_2 x_{t-2} + \cdots + \phi_p x_{t-p} + a_t + \theta_1 a_{t-1} + \cdots + \theta_q a_{t-q} \)
    \( x_t \): Observed Value of time \( t \).
    \( a_t \): IID noise term, assumed to be normally distributed
    \( \phi_i \): Autoregressive parameters
    \( \theta_i \): Moving average parameters
  • ARIMA (2,0,2)
  • Residual Normality Test
    - p-value: 0.618
OBE Message Distributor
Field Testing Scenarios_Impact Assessment

- March 2\textsuperscript{nd}-5\textsuperscript{th}, 2015
- 2 trucks with priority in northbound/southbound
- 2 buses with priority in eastbound/westbound
- 6 regular vehicles
- 10 rounds of testing

Source: Leidos Field Test Plan
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

Truck #1
Tuesday Afternoon: 1:30 pm - 5:00 pm

Diagram showing movement over time and space with different rounds marked.
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 #2

Truck #2
Wednesday Afternoon: 1:30 pm - 5:00 pm
DSRC Range vs. Geo Fencing Sections (MAP Nodes)

- Limitation of Map: WAVE Message Requirement (<1Kb)
  - Reducing Number of Lane Nodes
  - Reducing Number of Lanes on Egress Approaches
Performance Web Application (Cont.)
Conclusion

• Maricopa County DOT is a great partner in the Arizona Connected Vehicle Test Bed for CV research and development.

• A platform to support the design, development, implementation, and testing of CV applications including:
  • Intelligent Traffic Signal Control Application
  • Signal Priority Application
  • Pedestrian Assistance Application
  • Real-time Performance Observation Application

• Using latest standards in wireless communication and messaging

• Real-Time analysis of performance metrics by mode by movement
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Questions?