CoVASS Application in Urban Intersections

Breakout Session #21, AVS 2017
July 12, 2017

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Agenda

I. Connected & Automated Vehicles Project in Korea

II. Connected Vehicle Adaptive Signal control System (CoVASS)
I. Connected & Automated Vehicles Project in Korea
Contents

I.1 Overview

I.2 C-ITS Pilot Project

I.3 Connected & Automated Vehicles in Highway

I.4 Advanced Traffic Signal

I.5 Connected & Automated Vehicles in Urban Road System
I.1 Overview

MOLIT’s 2 Strategic Plan

Commercialization of C-ITS & C-AV Research

C-ITS

- R&D: Smart Highway (~2014)
- Pilot-Deployment: C-ITS Deployment (~2019)
- Commercialization: (2020~)

C-AV

- Highway: Cooperative Automated Road Sys. (~2020)
- Urban: CoVASS (Advanced Traffic signal, ~2018)
- Urban Cooperative Road Sys. (2018~)
I.2 C-ITS Pilot Project

| Purpose | • Verification of C-ITS Technologies and Services  
|         | • Preparation of Full-scale Deployment |

| Objectives | • C-ITS technology, safety applications and security systems Development  
|            | • Safety Benefit Evaluation, Economic Analysis  
|            | • Technical standards, Device Certification system, Legal System Improvement |

| Time Frame | • 2014. 7 ~ 2017. 12 |

| Budget | • 20 million U.S. dollars |

| Location | • Expressway, National Highway, Urban Road of Deajeon-City and Sejong-City (total 87.8km) |
C-ITS Pilot Project

1. Location Based Vehicle Data Collection
2. Location Based Traffic Information Provision
3. WAVE communication
4. Hazardous Location Notification
5. Road Feature and Weather Notification
6. Road Work Zone Warning
7. Signalized Intersection Violation Warning
8. Intersection Right Turn Conflict Warning
9. Transit Vehicle Operation Management
10. School Bus Warning System
11. School and Silver Zones Warming Data Collection
12. Pedestrian Collision Warning
13. Forward Collision Warning
14. Emergency Vehicle Approaching Alert
15. Vehicle SOS Service
Automated Vehicle Based Cooperative Automated Road System R&D (~2020)

- **LDM**
  - Key tech. which supports vehicles by providing dynamic traffic information based precise map

- **Hybrid V2X Communication**
  - Seamless/Long-Range communication tech. using both WAVE and LTE

- **Co-Automated Vehicle**
  - Cooperative Automated Vehicle using integrated positioning, in-vehicle sensor and wireless(V2X)

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**Block Diagram of R/D strategy**

**Automated Infra**
- Data
  - Support Decision
  - Share Data
- Link
  - Collection
  - Control
  - Cooperative
  - V2X Telecom

**Automated Vehicle**
- Perception
  - Enhance Perception
- Decision
  - Improve Decision and Control
- Control
  - Change road
  - Manage and more
  - Prediction
  - Judgement

**Operation, Law system**
- Support policy, law, standard and operation

**Vehicle based Tech.**
- Integrated process and control vehicle

**Road Based Technology**
- Upgrade road facility

**Testbed**
- Construct and verify Testbed

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**Demonstration in PyeongChang 2018 Winter Olympics**

**Location**
- Highway 50km
- Seoul TG ~ Hobeop JCT

**Goal**
- To make the safe, comfort environments for the autonomous Vehicles by connecting Vehicles and Road.

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I.4 Advanced Traffic Signal

I .5  Connected & Automated Vehicles in Urban Road System

Automated Vehicle Based Urban Cooperative Road System R&D (2018~)

Traffic Big Data
- Infra Data, Connected Car, Smart Phone

Center(Cloud)
- AI based Analysis (Super Computing)

Traffic Control
- CACC in Traffic Signal

5G, V2X DSRC
- Intersection Safety Support
- Real time HD Map
- See through (Cooperative local Mapping)
- Vulnerable Road User Discovery

Safety for Vulnerable Road User
II. Connected Vehicle Adaptive Signal control System (CoVASS)

- Dynamic signal phasing with cycle-free & local network offsets by V2X-i
  - Optimization of signal phase and offset based on real-time traffic condition
  - Equalization of queue growth across the ‘nxm’ network
### Ⅱ.1 Strategies for CoVASS

#### Signal Control Strategies
- **CoVASS algorithm by traffic flow conditions**

<table>
<thead>
<tr>
<th>Control range</th>
<th>Traffic flow conditions</th>
<th>Low Volume (LOS A, B, C)</th>
<th>Under-saturated (LOS D, E)</th>
<th>Saturated (LOS F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated</td>
<td></td>
<td>• Optimization by cycle</td>
<td>• Collection of traffic flow by V2X-i</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Control variables: cycle, green time, phase sequence</td>
<td>• Optimization of signal time in response to traffic flow per direction</td>
<td></td>
</tr>
<tr>
<td>Corridor</td>
<td></td>
<td>• Optimization of corridor</td>
<td>• Dynamic CI allocation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Critical Intersection (CI)</td>
<td>• Control the signal in response to traffic flow</td>
<td></td>
</tr>
<tr>
<td>Network</td>
<td></td>
<td>• Reflect the traffic situation across the network in real-time</td>
<td>• Route forecast</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Optimization of the network by providing an optimal route for each vehicle</td>
<td>• Network performance evaluation</td>
<td></td>
</tr>
</tbody>
</table>
Ⅱ.1 Strategies for CoVASS

Signal Control Strategies

- CoVASS isolated intersections
  - CoVASS controls the cycle length, the phase length and the green time ratio.
  - The algorithm applies a dynamic phase based on real-time share the road for intersections.
II.1 Strategies for CoVASS

Signal Control Strategies
- CoVASS isolated intersections
  - Arrival information calculation: vehicle arrival tables and stop delay tables
  - Optimal signal allocation: phase group lengths, phase lengths, and phase sequences

Vehicle Arrival Tables

- Distance to the stop line of individual vehicle
  \[ DR_{i,j,k} = L^i - Lc_{i,j,k} \]
  i = Vehicle number  
  j = link number  
  k = lane number

- Queue in a driving lane of individual vehicle
  \[ QL_{i,j,k} = L^i - Lc_{v_t=0}^{j,k} \]
  i = Vehicle number  
  j = link number  
  k = lane number

Time to stop line or queue
\[ AT_i = \frac{DR_{i,j,k} - QL_{i,j,k}}{v_t} \]
  i = Vehicle number  
  j = link number  
  k = lane number

Stop Delay Tables

- Stop delay
  \[ SD_{60}^{j,k} = \sum_{t=0}^{60} n_t^{j,k} \]
  \[ SD_{60}^{j} = \text{In } j \text{ link and } k \text{ lane, total stop delay during 60sec} \]
  \[ n_t^{j,k} = \text{In } t \text{ time, } j \text{ link, and } k \text{ lane, the number of waiting vehicles} \]
Ⅱ.1 Strategies for CoVASS

Signal Control Strategies

- CoVASS isolated intersections
  - Arrival information calculation: vehicle arrival tables and stop delay tables
  - Optimal signal allocation: phase group lengths, phase lengths, and phase sequences

Phase group lengths

- Calculate the phase group lengths through Webster method

\[
X_{g_{r_i}}^{\text{max}} = \max \left( G_{\text{min}}^{r_1} + G_{\text{min}}^{r_2}, \frac{1.5 \times L + 5}{1 - \sum_{i=1}^{n} y_i} \right)
\]

\[
\sum_{i=1}^{n} y_i = \frac{cn^{i2} \times S^{i2}}{t^{i2} \times S^{i2}} \times \frac{3600}{30}
\]

s.t.

\[
f_{g_i} = \max \left( cn^{11}, cn^{21}, cn^{52}, cn^{62}, cn^{71} \right)
\]

Phase lengths

- Determine the phase lengths through estimated rate of turn traffic flow

\[
G_{\text{max}} = \max \left( G_{\text{min}}^T, \left( X_{g_{r_i}}^{\text{max}} \times \frac{\eta_i^T}{n_i^T + n_i^L} \right) \right)
\]

\[
G_r^T = X_{g_{r_i}}^{\text{max}} - G_{\text{max}}
\]

Phase sequences

- Determine the phase sequences to minimize stop delay

\[
\text{first phase } T = \sum_{i=0}^{G_{2_1}^T} SD_{i}^T + \sum_{X_{g_{r_i}}^{\text{max}} - G_{\text{min}}^T} SD_{i}^T + [1.63 \times (n_i^T + n_i^L] \]

\[
\text{first phase } L = \sum_{i=0}^{G_{2_1}^T} SD_{i}^T + \sum_{X_{g_{r_i}}^{\text{max}} - G_{\text{min}}^T} SD_{i}^T + [1.63 \times (n_i^T + n_i^L] \]

\[
\min (\text{first phase } T, \text{first phase } L)
\]
Ⅱ.1 Strategies for CoVASS

- **Signal Control Strategies**
  - **CoVASS green coordinated**
    - CoVASS green coordinated enhances the isolated algorithm.
    - The algorithm identifies the critical intersections (CI) with high frequency of oversaturated.

<table>
<thead>
<tr>
<th>TOD</th>
<th>LOS</th>
<th>Network Average Delay (sec)</th>
<th>Network Average Number of Dtops</th>
<th>Network Average Stop Delay (sec)</th>
<th>Network Average Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>25.7</td>
<td>17.9</td>
<td>0.85</td>
<td>37.31</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>41.5</td>
<td>29.0</td>
<td>1.13</td>
<td>31.97</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>95.7</td>
<td>74.0</td>
<td>1.58</td>
<td>21.27</td>
</tr>
<tr>
<td>CoVASS</td>
<td>B</td>
<td>26.11</td>
<td>18.21</td>
<td>0.90</td>
<td>37.13</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>40.77</td>
<td>28.72</td>
<td>1.11</td>
<td>32.14</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>89.64</td>
<td>68.36</td>
<td>1.51</td>
<td>21.43</td>
</tr>
</tbody>
</table>
### Ⅱ.1 Strategies for CoVASS

#### Signal Control Strategies

- **CoVASS queue growth equalized**
  - Queue growth equalization (QGE) is proposed to determine the optimal traffic signal setting for oversaturated networks.
  - This can postpone gridlock activation by holding upstream queues.
  - Therefore, maintaining high network outflows for a prolonged duration.
### Ⅱ.1 Strategies for CoVASS

#### Signal Control Strategies

- **CoVASS queue growth equalized**

**Enhanced QGE**

#### Objective Function

Minimize

\[
\sum \sum (\max(\text{inflow rate} - \text{discharging capacity}, 0))^2
\]

\[
f(\phi_{i,k}, T^{\text{cycle}}_i) = \sum \sum (\alpha_{i,j} \hat{q}^{\text{in}}_{i,j} - q^{\text{out}}_{i,j} (t_{i,j} - \frac{T^{\text{loss}}_{i}}{T^{\text{cycle}}_i}))^2
\]

#### Constraint

Subject to

\[
h(\phi_{i,k}, T^{\text{cycle}}_i) = \sum_{k=1}^{c} \phi_{i,k} = 1
\]

\[
g(\phi_{i,k}, T^{\text{cycle}}_i) = \Phi^{\text{pede}}_{i,k} - \phi_{i,k} T^{\text{cycle}}_i \leq 0
\]

\[
0 \leq \phi_{i,k} \leq 1
\]

\[
30 \leq T^{\text{cycle}}_i \leq 180
\]

- Sum of phase rate = 1
- Insurance the minimum green times for pedestrian safety

<table>
<thead>
<tr>
<th>Signal phase</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
<th>$\phi_3$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase time</td>
<td>20</td>
<td>70</td>
<td>30</td>
<td>120</td>
</tr>
<tr>
<td>Phase rate</td>
<td>0.17</td>
<td>0.58</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>Min. green times</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>
## Ⅱ.1 Strategies for CoVASS

### Signal Control Strategies
- CoVASS queue growth equalized algorithm

![Diagram showing signal control strategies with spillovers]

<table>
<thead>
<tr>
<th>Link</th>
<th>Spillover Occurrence Time (sec)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Signal</td>
<td>Signal Optimization</td>
</tr>
<tr>
<td>② ← ③</td>
<td>1276</td>
<td>238</td>
</tr>
<tr>
<td>④ → ⑤</td>
<td>1435</td>
<td>1615</td>
</tr>
<tr>
<td>③ → ④</td>
<td>2871</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MOE</th>
<th>Current Signal</th>
<th>Signal Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Miles Traveled (VMT)</td>
<td>9927.72</td>
<td>10527.52 (6.0%↑)</td>
</tr>
<tr>
<td>Average speed (mph)</td>
<td>7.84</td>
<td>8.12 (3.6%↑)</td>
</tr>
<tr>
<td>Average delay (min/mile)</td>
<td>5.66</td>
<td>5.40 (4.6%↓)</td>
</tr>
</tbody>
</table>
II.2 V2X-i for CoVASS

Data Collection Strategies
- Vehicle data collection by ‘V2X-i + Radar’

Road Sensor
- Total vehicle travel time
- Near the intersection 150m

Data Integration of V2X-i and Road Sensor
- Total vehicle & Entire road ‘Travel time’
- Detect sensing technology convergence

RSE & OBU
- V2X OBU equipped vehicle ‘travel time’
- The entire road info. collecting

V2I

Traffic center
- Collection / judgment
- Signal Improvement
Data Collection Strategies

- Vehicle data collection by ‘V2X-i + Radar’
  
  > **Speed** (Individual vehicle speed)
  
  > **Position** (Coordinate based location information)
  
  > **Heading** (Direction of driving)
  
  > **Acceleration, Deceleration**
  
  > **Etc.**

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**Ⅱ.2 V2X-i for CoVASS**
II.3 Future Works for Urban Applications

- Pilot Project Plan for CoVASS Application in Urban Intersections
  - Dynamic signal phasing with cycle-free using V2X-i with radar detectors
  - Pedestrian detection using pedestrian sensor or push button
  - Area: 2 ~ 3 intersections with low traffic volume
This research was supported by a grant (No.16TLRP-C105654-02) from transportation logistics research program funded by Ministry of Land, Infrastructure and Transport of Korean government.

Thank you
The Capacity and Delay Implications of CAV at Signalized Intersections and How They Can be Accounted For in the Highway Capacity Manual Approach

Erik Ruehr, Alexander Skabardonis

San Francisco, July 12, 2017
Problem Statement

- Signalized Intersection Capacity and Operational Performance
  - Control settings/strategy
  - Vehicle characteristics
  - Communications

- Highway Capacity Manual Procedures
  - Use of “adjustment factors”
  - Example: Critical Intersection control strategy improves intersection capacity by 7%
  - Based on field data

- CAVs
  - Opportunities (examples)
  - Impact of penetration rates
  - Luck of field data
CV & Traffic Signals: Eco-Driving

Messages
“Here I am”

Signal Phase & Timing (SPaT)

Application: Dynamic Speed Advisory (source: UC & BMW)

14% Reduction in Fuel Use
Delay Savings
CAV & Traffic Signals: Dynamic Lane Grouping
CAVS & Traffic Signals: Saturation Headway

Average headway of mixed traffic VS penetration rate of AV

Theory vs Aimsun

- General scenario (theory)
- Best scenario (theory)
- Worst scenario (theory)
- General scenario (Aimsun)
- Best scenario (Aimsun)
- Worst scenario (Aimsun)
HCM Intersection Capacity Analysis Methodology

- Observe Operations to Determine Appropriate Parameters
- Data Collection
- Data Analysis to Determine Sensitivity of Input Parameters
- Develop Model
  Analysis supplemented by Simulation
- Calibrate Model based on Observed Data
- Validate Model
- HCM procedures
  Planning (*simple*) and Operations (*complicated*)
Intersection Capacity factors Affecting CAVs

- Saturation Flow Rate
- Lost Time
- Signal Settings
  - green time, cycle length
- Proportion of Vehicles Arriving on Green
- Approach Speed
Opportunities

- Provide advance information on signal operations to CAVs
- SPaT
- Dynamic lane allocation

- Reduce lost time

- Increase saturation flow rate

- Increase vehicle arrivals on green
Challenges

- Effect of advance information on CAVs is unknown until tested
- Operational Characteristics of CAVs not yet determined
- Impacts on intersection capacity and performance depend on CAVs penetration rate (*will change over time*)
- Intersection capacity may decrease for *autonomous* vehicles because of security concerns