Alternative Intersection Designs with Connected and Automated Vehicle

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Background

- Safety
  - 1.35 million people die each year as a result of traffic accidents since 2016
  - Intersection related crashes account for 36% and 43% in the U.S and EU27 countries, respectively

- Mobility
  - 6.9 billion hours of travel delay
  - $160 billion congestion cost

- Environment
  - 3.1 billion gallons of fuel wasted
  - 60 billion pounds of additional CO2
Tackling Intersection Congestion

- Optimize signal timing and phase (SPaT) plans
- Geometric reconfiguration
  - grade-separated interchange
  - alternative intersection design (AID)
- Adopt CAV technology (V2I intersection advisory, eco-driving, autonomous intersection management, etc.)
Alternative Intersection Designs

- Alternative geometric configuration
- Change conflict point composition
- Streamline traffic movements
- Reduce signal phases
CAV-AID Deployment in the Near Term

- 25-30 yrs. for CAVs to reach 95% penetration (Volpe National Transportation Center)
- AIDs have been growing steadily and gained recognition
- The driver's confusion could be remedied even with early-stage CAV technology
- A hybrid solution (CAV + AID) is one of the logical steps in the near term under mixed traffic conditions

DDI-Diverging diamond interchange
RCUT-restricted crossover U-turn
DLT-displaced left-turn, MUT-median U-turn, RDT-roundabout
## Benefits of CAV and AID

<table>
<thead>
<tr>
<th>Benefit</th>
<th>AID</th>
<th>CAV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection conflict pt. reduction</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Signal phase reduction</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Streamline traffic movement</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Short following headway</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>No start-up lost time</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>Synchronously discharge</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>Driver’s confusion prevention</td>
<td></td>
<td>Y</td>
</tr>
</tbody>
</table>
Simulation Study for DDI

- Two improvements for mobility
  - Conversion to DDI from CDI
  - Introduction of CAV
- DDI interchange at State Highway 72 (DE-72) and US Highway 13 (US-13)
- Simulation conducted in PTV Vissim with its Driver Model API

<table>
<thead>
<tr>
<th></th>
<th>CDI</th>
<th>DDI</th>
<th>CAV</th>
<th>MPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base-CDI</td>
<td>✓</td>
<td></td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>Base-DDI</td>
<td>✓</td>
<td></td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>CAV-CDI</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>10%-100%</td>
</tr>
<tr>
<td>CAV-DDI</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>10%-100%</td>
</tr>
</tbody>
</table>

Simulation network

<table>
<thead>
<tr>
<th></th>
<th>Longitudinal Control</th>
<th>Lateral Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Driver</td>
<td>Calibrated Wiedemann 99</td>
<td>Vissim default</td>
</tr>
<tr>
<td>CAV</td>
<td>Intelligent Driver Model (IDM)</td>
<td>Vissim default</td>
</tr>
</tbody>
</table>

Simulation scenarios

Vehicle behavior
Simulation Study for R-CUT

- Assess the Impact of driver’s confusion
- Traffic sensors placed at three locations: upstream, diverging, and downstream location
- Behavior caused by driver’s confusion
  - Sudden slow-down at the ramp pocket lane (diverging area)
  - Abrupt lane change as approaching the end of the pocket lane

<table>
<thead>
<tr>
<th>Case</th>
<th>CAV</th>
<th>Percentage of confused drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>5%-20%</td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
<td>0%</td>
</tr>
</tbody>
</table>

Simulation network

Simulation scenarios
With DDI, the intersection throughput increases to 5,350 vehicle per hour (vph) from 4,400 vph, with decrease in deviation.

CAV contributes less to the increase in intersection throughput at tested scenarios.

The average vehicle delay has similar trends.

The DDI offers a systematic reduction (40 s per vehicle) with less deviation.
Results-RCUT Traffic Flow

- Flow-speed characteristic is observed at upstream, diverging, and downstream locations.
- The performance increase at the diverging and downstream location with CAV.
- The segment carrying capacity increased to 2,100 vph per lane (from 1,500 vph per lane).
Results-RCUT Traffic Flow

- Behavior induced by driver’s confusion
  - Sudden slow down
  - Abrupt lane change
- A 250-m section extracted from the diverging area
- The shockwave was created due to the induced behaviors
Results-Impact of Driver’s Confusion

- ANOVA test with post-hoc Tukey’s method at 95% confidence level
- The pairwise difference among the 5 levels (0% - 20%) of confused driver for DDI and RCUT
- The difference in average vehicle delay are statistically significant.

TABLE IV: ANOVA Test for Average Vehicle Delay in RCUT

<table>
<thead>
<tr>
<th>Confused Driver Rate</th>
<th>N</th>
<th>Delay, s/veh</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>360</td>
<td>12.2</td>
<td>A</td>
</tr>
<tr>
<td>5%</td>
<td>360</td>
<td>28.65</td>
<td>B</td>
</tr>
<tr>
<td>10%</td>
<td>360</td>
<td>39.36</td>
<td>C</td>
</tr>
<tr>
<td>15%</td>
<td>360</td>
<td>43.45</td>
<td>D</td>
</tr>
<tr>
<td>20%</td>
<td>360</td>
<td>48.79</td>
<td>E</td>
</tr>
</tbody>
</table>

TABLE V: ANOVA Test for Average Vehicle Delay in DDI

<table>
<thead>
<tr>
<th>Confused Driver Rate</th>
<th>N</th>
<th>Delay, s/veh</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>360</td>
<td>81.42</td>
<td>A</td>
</tr>
<tr>
<td>5%</td>
<td>360</td>
<td>82.44</td>
<td>B</td>
</tr>
<tr>
<td>10%</td>
<td>360</td>
<td>83.54</td>
<td>C</td>
</tr>
<tr>
<td>15%</td>
<td>360</td>
<td>84.41</td>
<td>D</td>
</tr>
<tr>
<td>20%</td>
<td>360</td>
<td>85.78</td>
<td>E</td>
</tr>
</tbody>
</table>
Conclusions

- **Mobility**
  - **DDI:** The introduction of CAV only increase the throughput by 7% for CDI and 2% for DDI
  - **DDI:** The conversion to DDI provides 20% throughput increase (4,400 vph to 5,350 vph)
  - **RCUT:** A flow-stable region in the speed-flow curve with higher capacity (1,500 vph/ln to 2,000 vph/ln)

- **Drivers’ confusion**
  - Significant impact was observed for avg. delay in the presence of driver’s confusion.
Future Research

- **SPaT optimization** for AIDs
- **Optimization of CAV operation**: eco-driving, V2I integration, adaptive signal control, signal-free autonomous intersect management
- **Validate** drivers’ confusion with field data
- **Simulation scope**: expand evaluation scope to corridor- and network-level
Thank you for your time!

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