Adaptive Control Strategy of Variable Speed Limit on Freeway Segments under Fog Conditions

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Shorter reaction space

Sharp braking

aggressive actions

speed difference

crash risk

Background Methodology Simulation Results & Discussions Conclusions
Speed management measure: Variable Speed Limit (VSL)

Existing weather-related VSL control:
- Pre-defined speed limit according to different levels of weather conditions

Key questions
- How to determine the speed displayed on the sign?
- How the VSL adapts to the changes in the environment?
Objective

Develop a VSL control strategy under fog conditions so that it can adapt to changes in the external environment.

External environment

- Traffic flow
- Weather condition
- Road geometric condition

VSL control strategy

- Traffic safety risk
- Control logic
- Key control parameters
Framework of the proposed VSL control strategy

- Establish the relationship
- Evaluate the safety effect
- Simulate the traffic flow state
- Evaluate the mobility effect

Methodology

Data preparation
- Weather data
- Traffic flow data
- Road geometric data
- Crash data

Crash prediction model
- Input
- Feedback

Traffic simulation model
- Input

VSL control effects
- Adjust

VSL control strategy

Optimal VSL control strategy under fog conditions

• Problem formulation
• Optimization solver

Model predictive control
(1) Crash prediction

Bayesian logistic regression

\[ y_i \sim \text{Bernoulli}(p_i) \]
\[ p_i = P(y_i = 1) = \frac{e^{\eta_i}}{1 + e^{\eta_i}} \]
\[ \eta_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ji} \]

- Input: variables of three types of factors
- Output: traffic crash risk (defined as the probability of a crash)
- The model is trained by historical data

Simulation Methodology Background Results & Discussions Conclusions
(2) Traffic simulation

**Modified cell transmission model (MCTM)**

\[ \rho_i(k+1) = \rho_i(k) + \Delta t / l_i \left( q_i(k) - q_{i+1}(k) + r_i(k) - f_i(k) \right) \]

- \( \rho \): traffic density
- \( q \): transfer flow
- \( r \): on-ramp flow
- \( f \): off-ramp flow
- \( \Delta t \): time step
- \( l \): cell length

- A macroscopic traffic simulation model -- MCTM
- The road segment is divided into cells
- Each cell is characterized by its traffic fundamental diagram (FD)
- The speed limit affects the transfer flow between adjacent cells
(3) VSL control logic

Processes:
1. Data collecting
2. Risk threshold judgment
3. Activate VSL control or Recover to original speed limit

Key factors:
1. the start threshold
2. the control cycle of VSL, \( T \)
3. the speed change step, \( \Delta v \)
4. the maximum speed difference between signs, \( \Delta V_m \)
(4) Determination of optimal VSL control factors

**VSL control goal**
effectively reduce traffic safety risk under low visibility without significantly increasing the total travel time (TTT).

**Decision variables:**
- $T, \Delta v, \Delta V_m$

**Objective function:**
- $Fitness = -\Delta R / \Delta T$

\[
\Delta R = (R_{VSL} - R_{Non}) / R_{Non}
\]

\[
\Delta T = (TTT_{VSL} - TTT_{Non}) / TTT_{Non}
\]

- $R = \sum_{k=1}^{h} \sum_{i=1}^{n} Risk_i(k) / TTT$

- $TTT = \sum_{k=1}^{h} \sum_{i=1}^{n} l_i q_i(k) / v_i(k)$

The optimization is solved by Genetic Algorithm (GA)

**Crash prediction model**

**Traffic simulation model**

**Background**

**Methodology**

**Simulation**

**Results & Discussions**

**Conclusions**
### Study area

- **5/6 lanes (1 HOV lane)**
- **3 On-ramps & 1 Off-ramp**
- **I-405 (N), Orange, CA, US**
- **2.7 miles**

<table>
<thead>
<tr>
<th>MLu 9.77</th>
<th>ML1 10.67</th>
<th>ML2 11.02</th>
<th>ML3 11.37</th>
<th>ML4/MLd 12.48</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ1</td>
<td>0</td>
<td>ρ2</td>
<td>ρ3</td>
<td>ρ4</td>
</tr>
</tbody>
</table>

**Legend:**
- ML: mainline
- ρ: loop detector
- ON/OFF: on-ramp/off-ramp
- MLX: absolute postmile indices
- HOV: High-Occupancy Vehicle
Traffic flow data

- Caltrans PeMS
- Loop detector data
- Road geometric data

Traffic crash data

- Transportation Injury Mapping System (TIMS)

Weather data

- NOAA
- Local climatological data

These data are matched based on the time and space and integrated into a new dataset.
(1) Development of crash prediction model

<table>
<thead>
<tr>
<th>Category</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>Visibility</td>
<td>1 for diverge segment; 0 for otherwise</td>
</tr>
<tr>
<td>Road</td>
<td>DS</td>
<td>Average flow at upstream</td>
</tr>
<tr>
<td></td>
<td>AQD</td>
<td>Average flow at downstream</td>
</tr>
<tr>
<td>Traffic flow</td>
<td>DQU</td>
<td>Standard deviation of flow at upstream</td>
</tr>
<tr>
<td></td>
<td>DVU</td>
<td>Standard deviation of speed at upstream</td>
</tr>
<tr>
<td></td>
<td>DQD</td>
<td>Standard deviation of flow at downstream</td>
</tr>
<tr>
<td></td>
<td>DVD</td>
<td>Standard deviation of speed at downstream</td>
</tr>
<tr>
<td></td>
<td>DV</td>
<td>Speed difference between upstream and downstream</td>
</tr>
</tbody>
</table>

\[
Risk_i(k) = 0.493 - 0.202 \text{Visibility} - 1.077DS + 0.002AQD + 0.173DQU - 0.202DVU - 0.009DQD - 0.561DVD + 0.013DV
\]

Traffic risk for each cell of each time step can be calculated by the equation.
(2) Development of MCTM

- MAPEs of four cells are all less than 10%
- The MCTM can be used to simulate the evolution of the traffic flow
(3) Evaluation of VSL control strategy

Optimal VSL Control Factors under Two Conditions

<table>
<thead>
<tr>
<th>Optimal control factors</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sunny</td>
</tr>
<tr>
<td>start threshold</td>
<td>0.2</td>
</tr>
<tr>
<td>control cycle (s)</td>
<td>150</td>
</tr>
<tr>
<td>speed change step (mph)</td>
<td>10</td>
</tr>
<tr>
<td>maximum speed difference between neighboring signs (mph)</td>
<td>15</td>
</tr>
</tbody>
</table>

- The VSL under sunny condition has larger control cycle and speed change step.
- The VSL under fog conditions changes speed limit more cautiously.

VSL control effects

<table>
<thead>
<tr>
<th>VSL control effects</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sunny</td>
</tr>
<tr>
<td>Δ% of risk</td>
<td>-25.44</td>
</tr>
<tr>
<td>Δ% of TTT</td>
<td>2.89</td>
</tr>
</tbody>
</table>

- The proposed VSL reduces traffic risk without significantly decreasing mobility.
An example: Risk change of Cell 4 under fog conditions

- Two peaks in the risk curve are reduced by VSL control
- The VSL control can reduce high-risk states
- Risk for cell 4 is reduced by 37.15% with VSL control
(4) Effects of Placements of VSL Signs

**Simulation Methodology**

**Background**

**Conclusions**

### Benifit-cost ratio

\[ \text{Benifit-cost ratio} = \left(-\frac{\Delta R}{\Delta T}\right) / M \]

- \( \Delta R \): change of risk
- \( \Delta T \): change of TTT
- \( M \): the number of the VSL signs

**Placement scenarios of VSL signs**

**Effects of the placements of VSL signs**
Conclusions

- The VSL control strategy under fog conditions changes speed limit more cautiously.
- It effectively reduced traffic safety risks without significantly decreasing mobility.
- Scenario 1 (each cell has one VSL sign) can balance the benefits and costs.

Future work

- The effect of the drivers’ compliances
- The speed coordination between the first VSL sign and the upstream
Thanks for your time!

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