Source: FHWA.

Source: FHWA.

Source: FHWA.

Source: FHWA.

Driving Innovation

Modeling Speed Adaptation of Connected Drivers with Infrastructure-to-Vehicle (I2V) Variable Speed Advisory

Transportation Research Board (TRB)
Workshop on Traffic Simulation and Connected and Automated Vehicle (CAV) Modeling
November 16–18, 2020

Presenters: Hao Liu and Xiao-Yun Lu
California Partners for Advanced Transportation Technology (PATH), UC Berkeley

John Halkias and Gene McHale
Federal Highway Administration (FHWA)

U.S. Department of Transportation
Federal Highway Administration

SAXTON LABORATORY

Disclaimer

This presentation was created and is being copresented by both FHWA and a contractor. The views and opinions expressed in this presentation are the presenters' and do not necessarily reflect those of FHWA or the U.S. Department of Transportation (USDOT). The contents do not necessarily reflect the official policy of the USDOT.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this presentation only because they are considered essential to the objective of the presentation. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

Background

- **Variable Speed Advisory** (VSA): highway speed harmonization and vehicle energy saving.
  - Rely on fixed sensors: delayed detection of congestion.
  - Use message signs at fixed locations: constrained speed control region.
- **Connected Vehicle** (CV) Technology: better traffic perception and increased control capabilities of VSA applications.
  - Timely update of the traffic state via CV information.
  - Distribution of VSA messages via I2V communications.
  - Partially connected vehicle fleet—not every vehicle can obtain VSA messages via onboard feedback.
  - Uncertainties in driver compliance—drivers might not completely follow the VSA.

Objectives

Develop a **connected manually driven vehicle** (CMDV) model:

- Depict CV drivers' speed adaptation due to VSA.
- Model drivers' compliance level in different traffic conditions.
- Integrate with existing simulation framework for modeling mixed traffic.

CMDV model developed based on an existing human-driven vehicle (HV) car-following model:

- Stimulus response model paradigm to capture speed behavior adaptation.
- Existing model framework with calibrated parameters.
- Real-world freeway network for model evaluation.

Longitudinal Movements of CMDVs

Free acceleration term: $a_F = a_{Max}\left[1 - \left(\frac{v(t)}{V_0}\right)^{\gamma}\right]$

a_F : free acceleration; a_{Max}: maximum acceptable acceleration; $v(t)$: current speed; V_0: desired speed; γ: model parameter.

V_0 is the driver behavior parameter that affects the free acceleration term.

V_0 represents a driver's speed choice under free-flow conditions.

- Speed limit.
- Variable speed limit (VSL) or VSA.
- Onboard CMDV information.
- Compliance level.

Speed Adaptation of CMDVs

Modeling the impacts of CMDV on V_0:

- CMDV driver's desired speed: $V_0(t) = V_j^*(t) + \sigma + \varepsilon$

  $V_0(t)$: desired speed at time t; $V_j^*(t)$: VSA of the current road section at time t; σ: random speed fluctuation around a target speed; ε: compliance to the advisory speed; j: freeway section ID.

  - σ depicts human drivers' (unconscious) speed fluctuation while driving.
  - ε affects the effectiveness of the CMDV ($\varepsilon = 0$: completely comply with the VSA).

- Algorithm to **generate VSA** based on traffic conditions.
- Adoption of **VSA field test data** to obtain the distribution of ε.

Speed Adaptation of CMDVs

- Step 1: bottleneck identification:

  $\bar{v}_j(k) \le V_T$, $\bar{v}_j$: measured speed; V_T: threshold speed; k: update time.
- Step 2: VSA for the bottleneck section *j* :

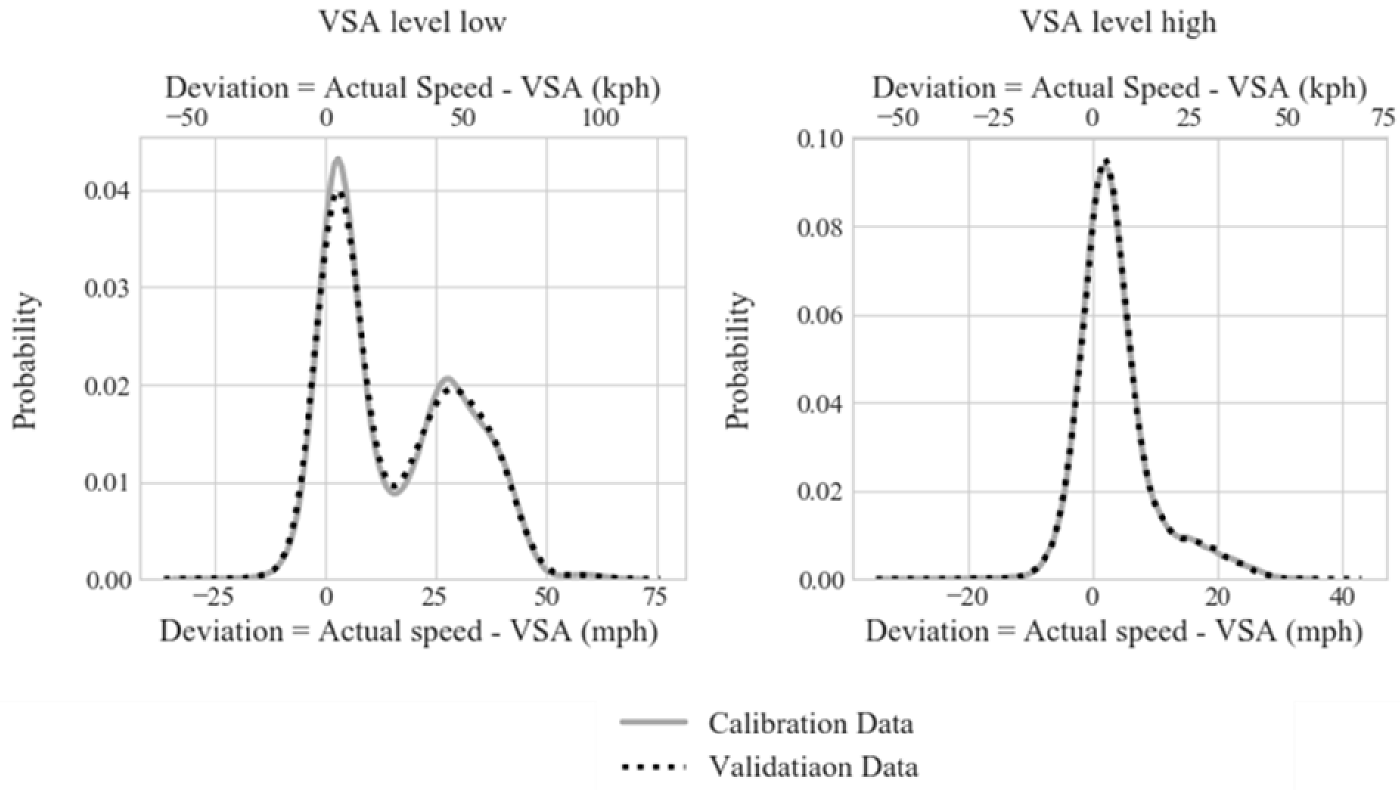
  $V_j(k) = \bar{v}_j(k-1) + \begin{cases} \varsigma_{o1} \cdot \big(O_c - O_j(k)\big) & O_j(k) < O_c \\ \varsigma_{o2} \cdot \big(O_c - O_j(k)\big) & O_j(k) \ge O_c \end{cases}$, V_j : VSA for section *j*; $\bar{v}_j$: measured speed of the bottleneck; O_c: critical detector occupancy; O_j: measured occupancy; ς_{o1} and ς_{o2}: unitless control gains.
- Step 3: VSA for the upstream sections:

  Use above equation, replacing O_j with $\bar{O}_j = \rho_1 \cdot O_j + \rho_2 \cdot O_{j+1} + \rho_3 \cdot O_{j+2}$, weighted occupancy estimated using a semiglobally looking ahead algorithm; ρ: weights for computing the weighted occupancy
- Step 4: Application of change constraints:

  $\left|V_j(k) - V_j(k-1)\right| \le V_S$, $\left|V_j(k) - V_{j+1}(k)\right| \le V_S$, $V_{min} \le V_j(k) \le V_{max}$, V_S: a step speed for VSA change; V_{min}: minimum VSA level; V_{max}: maximum VSA level

Model Validation

- The distribution of ε can be derived from field speed data observed near VSA signs.
- Empirical data show distinct curves for the two groups: VSA greater than 35 and less than 35 miles per hour (mph).
- Apply empirical cumulative distribution function to generate random samples in simulation.



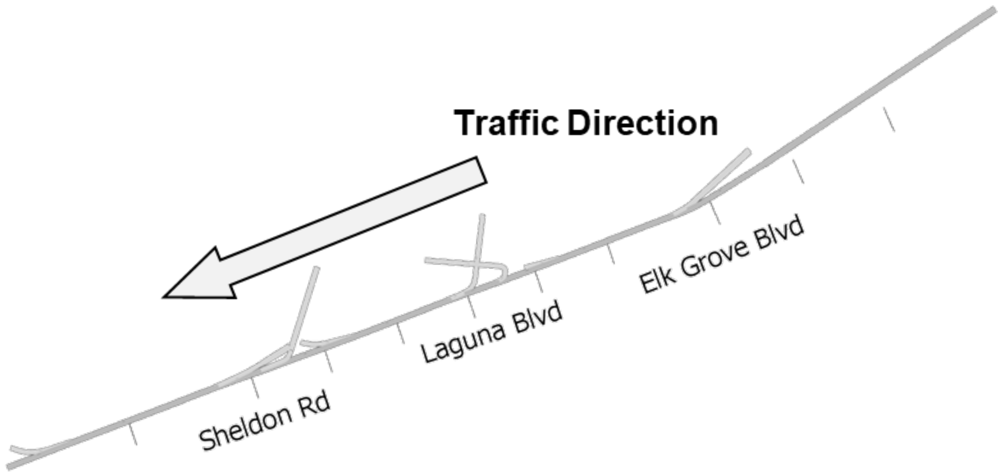
Source: FHWA.

U.S. Department of Transportation
Federal Highway Administration

Simulation Analysis

Study corridor:

State Route 99 (SR-99) in Sacramento, CA.



Source: FHWA.

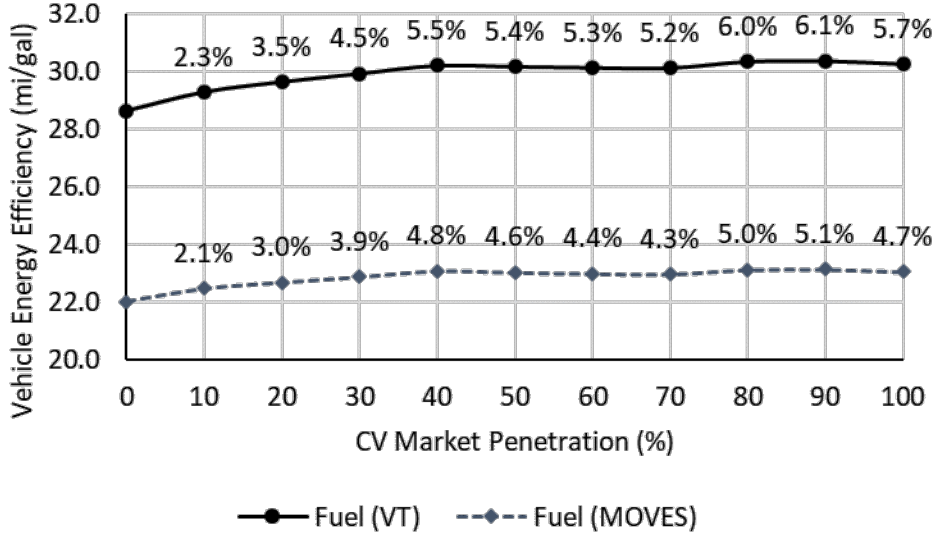
- This is a 7-mile corridor.
- The corridor has three on-ramps with merge bottlenecks.
- Most of the downstream bottlenecks cause severe congestion.
- The simulation period is 4:00 a.m.–12:00 p.m., which covers the entire morning peak.
- The vehicle energy consumption is estimated by the Motor Vehicle Emission Simulator (MOVES) model and the Virginia Tech Comprehensive Power-Based Fuel Consumption Model (VT).

U.S. Department of Transportation
Federal Highway Administration

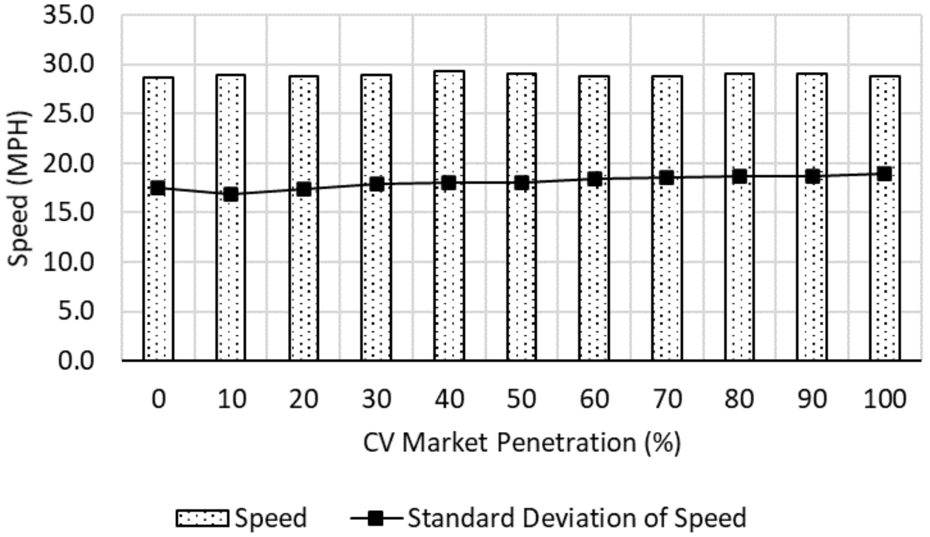
Simulation Analysis

Impacts of CMDV market penetration rate:

- CMDV harmonizes traffic flow, leading to improvement of vehicle fuel efficiency.
- Improvement stabilizes when the CMDV market penetration is 40 percent or higher.
- Minor change exists in speed and speed standard deviation with CMDV market penetration.
- Two effects of CMDV are:
  - Reducing traffic speed upstream from bottleneck led to lower average speed.
  - Increasing bottleneck throughput by reducing the bottleneck congestion led to higher average speed.



Source: FHWA.



Source: FHWA.

U.S. Department of Transportation
Federal Highway Administration

Simulation Analysis

Impacts of driver compliance:

- Full compliance level adds 2 to 3 percent energy benefit, regardless of the CMDV market penetration rate.
- Factors that prevent further freeway performance improvement need to be identified.

CMDV MPR (%)	Compliance Increase (%)	Fuel Efficiency from MOVES (mi/gal)	Fuel Efficiency from VT (mi/gal)	Vehicle Speed (MPH)	Std of Vehicle Speed (MPH)
10	0	22.5	29.3	28.9	16.9
10	100	22.8 (+1.7%)	29.7 (+1.6%)	28.9 (+0.1%)	16.0 (-5.5%)
20	0	22.7	29.6	28.8	17.4
20	100	23.2 (+2.4%)	30.3 (+2.2%)	28.8 (0.0%)	16.2 (-6.9%)
100	0	23.0	30.2	28.8	18.9
100	100	23.7 (+3.1%)	31.0 (+2.6%)	28.6 (-0.7%)	18.2 (-3.4%)

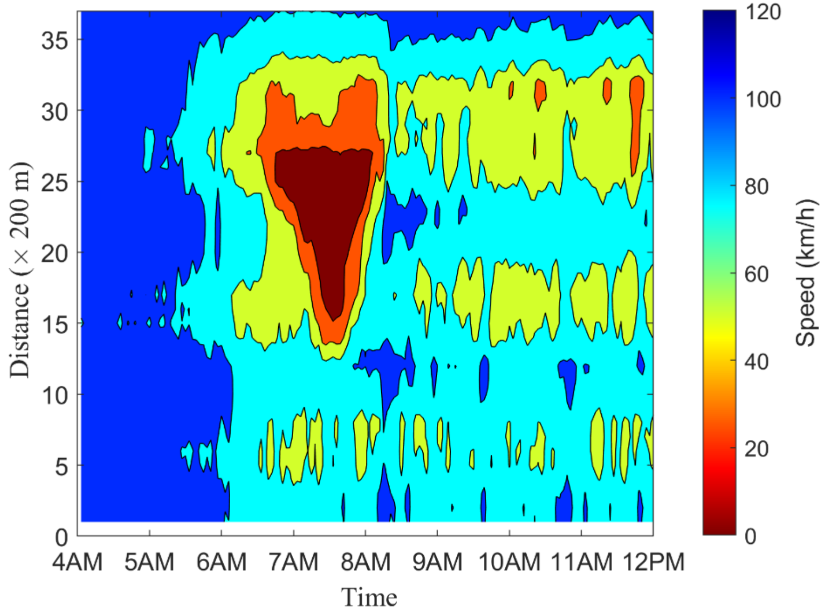
Source: FHWA.

Std: standard deviation

Simulation Analysis

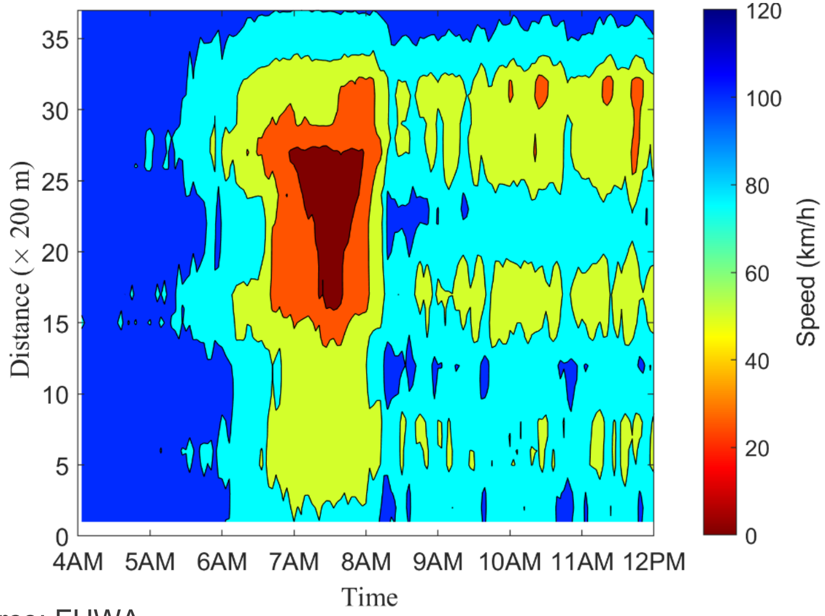
Impacts of driver compliance:

- Further increasement of the driver compliance result in traffic pattern change.
- Positive and negative aspects of such changes.



Source: FHWA.

20 percent CMDV MPR
Baseline Compliance



Source: FHWA.

20 percent CMDV MPR
Full Compliance

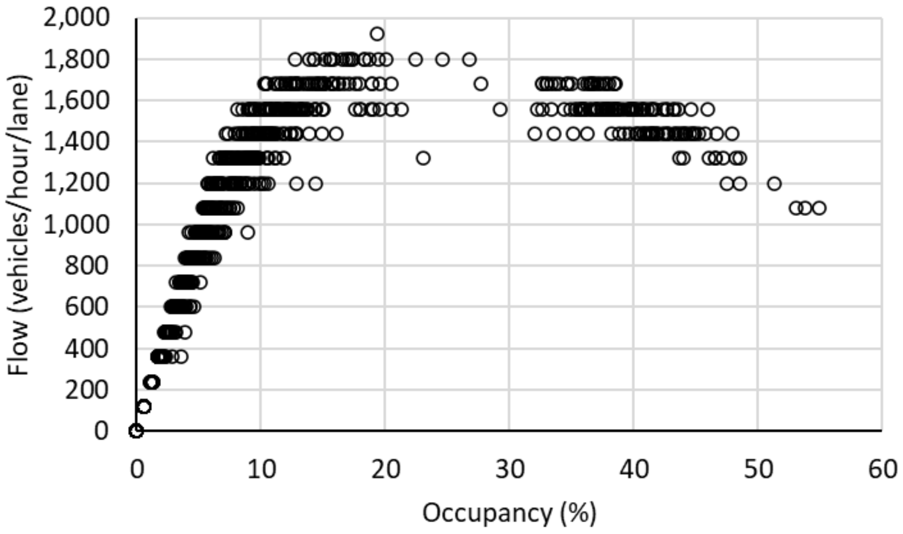
U.S. Department of Transportation
Federal Highway Administration

Simulation Analysis

Impacts of driver compliance:

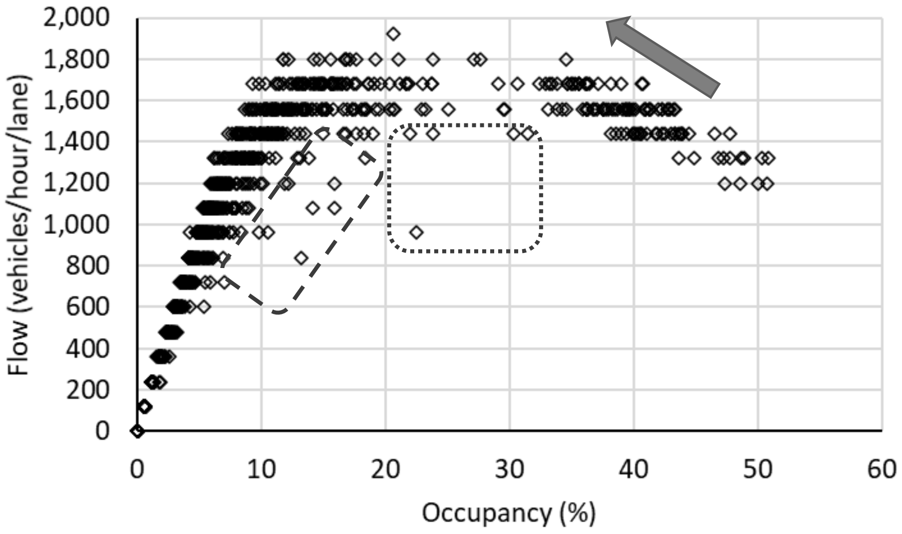
- Positive effect: Points on bottleneck fundamental diagrams shift left and upward, leading to throughput increase.
- Negative effect: Underuse of the capacity in boxes create a delayed response of VSA.

Need predictive algorithms for improvement.



Source: FHWA.

20 percent CMDV MPR
Baseline Compliance



Source: FHWA.

20 percent CMDV MPR
Full Compliance

U.S. Department of Transportation
Federal Highway Administration

Summary

- Development of a CMDV model to depict human drivers' behavior adaptation due to the in-vehicle information.
- Implementation of a feedback VSA for speed management via I2V communications.
- Calibration and validation of the CMDV model parameters to reflect drivers' compliance with the CMDV speed advisory.
- Sensitivity analyses for depicting the CMDV effectiveness.
- Implementation of the model in state-of-the-art simulation environment.

Questions?

John Halkias
Government Task Manager
✉ John.Halkias@dot.gov

Gene McHale
Case Study Leader
✉ Gene.McHale@dot.gov

Source: FHWA.

U.S. Department of Transportation
Federal Highway Administration