Combined Variable Speed Limit (VSL) and Coordinated Ramp Metering (CRM) Control Design for Freeway Traffic

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Outline

- Control Strategy: Maximizing Bottleneck Flow
- Method to Design Combined VSL and CRM
- Integrated Traffic Control Simulation Platform (ITCSP)
- Next Steps
Control Strategy: Bottleneck Flow Limited by Feeding Flow

Why is Bottleneck flow below capacity if its upstream is congested?

Answer: Because the feeding flow into the bottleneck is low – even if the speed is increasing along the bottleneck, the density is decreasing.
Control Strategy: Maximizing Bottleneck Feeding Flow

- **Control strategy:** to maximize bottleneck flow;
- **Only two possible situations due to flow conservation:**
  - Bottleneck can be modeled as lane drop
  - Able to create a long discharge section upstream of bottleneck
- **Example:** flow of 3-lane discharge section upstream is closer to (a 2-lane) bottleneck capacity flow
Example – I-80 W in PM Peak
Benefit of Maximizing Bottleneck Flow

\( Q_b(t) \) – Bottleneck capacity flow; 
\[ A_f(t) = \int_{t_0}^{t_1} Q_b d\tau = Q_b(t_1 - t_0) \]

\( q_{\text{cong}}(t) \) – congested discharge flow; 
\[ A_{\text{cong}}(t) = \int_{t_0}^{t_1} q_{\text{cong}}(\tau) d\tau \]

\( q_{\text{contr}}(t) \) – controlled traffic flow; 
\[ A_{\text{contr}}(t) = \int_{t_0}^{t_1} q_{\text{contr}}(\tau) d\tau \]

Cumulative flow

\( q_{\text{cong}}(t) \approx Q_b \)

\( q_{\text{contr}}(t) \to Q_b \)

\( q_{\text{cong}}(t) < Q_b \)

\( t_0 \quad t_{\text{contr}} \quad t_1 \)
Control Design

- Control Design Approach and Philosophy
- VSL Design – *Ad hoc*, Non-Model Based
- CRM Design – Model Based
- Macroscopic Simulation
- Microscopic Simulation
Control Design Approach and Philosophy

- Determine VSL first and then determine CRM strategy based on known speed limit
- Leads to system decoupling and linearization
- Advantages:
  - VSL selection takes most important practical constraints into account including onramp factors
  - VSL is very robust
  - VSL is higher level design and leaves more space for CRM for optimization
  - CRM design becomes a linear optimization problem
  - CRM allow fast rate change but VSL does not
Control Design Approach and Philosophy

- To solve practical problems
- Critical VSL location is a controlled discharge point
- Requires less detection although more detection could improve its performance
- Certain level macroscopic control – 10s~30s aggregation level
VSL Design Approach and Philosophy

- The following factors have been taken into account:
  - Driver acceptance, safety, energy use and emissions
    - Limit on speed variation over time
    - Limit on speed variation over space
  - Demand and capacity flow of onramp
  - Demand and capacity of each link of mainline
  - Off-ramp flow
  - Onramp storage capacity and estimated queue length
  - Maximizing the feeding flow to the bottleneck
  - Addressing possibility of creating queue upstream
Notations

\( m \) – link index; \( M \) – Critical VSL Control link index; \( M+1 \) discharge link index;
\( k \) – time index
\( m_0 \) – index of the most upstream link affected by the bottleneck; \( m_0 \) could be a negative integer;
\( m_h \) – link index of the congestion head
\( m_t \) – link index of the congestion tail
\( V_f \) – free-flow speed
\( V_c \) – speed of congested flow for saturated traffic in the queue upstream of the Critical VSL
\( q_{M+1}, v_{M+1} \) – flow and speed at the discharge section
\( u_m \) – desired VSL at link \( m \), to be designed
\( L_m \) – length of link \( m \)
\( Q_m \) - mainline capacity of link \( m \), known
\( Q_b \) – bottleneck capacity flow, known or estimated
\( Q_{m,o} \) – onramp \( m \) capacity, known
\( d_m \) - demand from onramp \( m \), measured or estimated
\( q_m(k) \) - estimated main lane flow at time \( k \)
Notations

\( \bar{q}_m(k-1) \) – measured flow at time \( k-1 \)
\( \bar{v}_m(k) \) – measured speed of link \( m \) at time \( k \)
\( s_m(k) \) – off-ramp \( m \) flow, measured;
\( L_{m,o} \) – onramp \( m \) length, known;
\( u_M(k) \) – Critical VSL immediately above the discharge link, to be designed
\( u_0(k) \) – speed in the most upstream relevant link
\( \gamma \) – gain parameter to be determined in simulation
\( O_c \) – critical occupancy
\( \rho_c \) – critical density
\( \bar{\rho}_{M+1} \) – discharge link density, measured/estimated
\( r_m(k) \) – metering flow rate (veh/hr), to be designed
\( s_m(k) \) – total off-ramp flow rate (veh/hr), measured
\( N_p \) – prediction steps for each \( k \) in Model Predictive Control
Method 3: VSL Design 1 for Stage 1

- **Stage 1: Congestion begins** \( m_h = m_t = M \),

- **VSL design**
  - using one link for Critical VSL Control \( u_M \)
  - for the congestion tail section \( [m_0, M] \): speed monotonically decreasing
Snapshot of VSL Strategy 1: at Stage 1

\[ L_M = L_{m_h} = L_{m_t} \]

\[ u_0 = V_f \]

Bottleneck

[Diagram showing the relationship between time \( t \) and \( L_0 \), \( L_m \), \( L_M \), and \( V_d \).]
Method 3: VSL Design 1 for Stage 2

- **Stage 2**: After applying VSL control at \( m_h = m_t = M \), traffic congestion may be moving further upstream:

  \[
  m_0 \leq m_t < m_h = M
  \]

- **VSL design for the three sections:**
  - for the congestion tail section \([m_0, m_t]\): speed monotonically decreasing
    - using one link for Critical VSL Control \(u_M\)
  - for the congested section, \([m_t, m_h]\): using constant speed for harmonization
Method 3: VSL Design 2 for Stage 2

- An Alternative Approach for Stage 2:

\[ m_0 < m_t < m_h < M \]

- VSL design for the three sections:
  - for the congestion tail section \([m_0, m_t]\): speed monotonically decreasing
  - Using several link for Critical VSL control \([m_h, M]\): speed monotonically increasing to meet the discharge flow section demand requirement
  - In between \([m_t, m_h]\): Constant speed for harmonization
VSL Design – Constraints

- **Equity issues along the corridor**
  - Difference and variation in demand from arterials
  - Onramp storage capacity

\[
\lambda_M q_M (k) = Q_b \\
0 \leq u_m (k) \leq \bar{V}_f \\
u_m (k) \leq u_{m-1} (k) \\
u_m (k-1) - 5 \leq u_m (k) \leq u_m (k-1) + 5
\]

- **Dynamic design based model likely to cause infeasibility problem**
VSL Design – Speed Decreasing at Stage 1

\[ u_{m+1}(k) = u_m(k) + \max\left\{ -5, \min\left\{ (\eta \alpha_m(k) + (1-\eta) \beta_m)\left[ u_M(k) - u_{m_0}(k) \right], 0 \right\} \right\} \]

\[ m_0 < m_h = m_i = M \]

\[ u_0(k) = V_f \]

\[ q_m(k) = \bar{q}_{m-1}(k-1) + R_m(k) - s_m(k) \]

\[ R_m(k) = \min\{ d_m(k), Q_{m,o}, Q_m - \bar{q}_{m-1}(k-1) \} \]

\[ \alpha_m(k) = H(Q_m - q_m(k)) \]

\[ \beta_m = H(1/L_{m,o}) \]

\[ 0 \leq \eta \leq 1 \]
VSL Design – Speed Decreasing at Stage 2

\[ u_m(k) = u_{m-1}(k) + \]
\[ \max \left\{ -5.0, \min \left\{ (\eta \alpha_m(k) + (1-\eta) \beta_m) \left[ u_m(k) - u_{m_0}(k) \right], 0 \right\} \right\} \]
\[ u_{m_0}(k) = V_f \]
\[ R_m(k) = \min \left\{ d_m(k+1), Q_{m,o}, Q_m - \bar{Q}_{m-1}(k-1) \right\} \]
\[ q_m(k) = \bar{Q}_{m-1}(k-1) + R_m(k) - s_m(k) \]
\[ \alpha_m(k) = H(Q_m - q_m(k)) \]
\[ \beta_m = H\left(1/L_{m,o}\right) \]
\[ 0 \leq \eta \leq 1 \]
Snapshot of VSL Strategy 2: Gradually Increasing to $u_M$

- Bottleneck

$V_d$

$V_c$

$V_f$

$VSL_t$

$VSL_h$

$L_M$

$L_{m_h}$

$L_m$

$L_{m_i}$

$L_0$
VSL Design – Speed Increasing at Congestion Head

\[ u_{m-1}(k) = u_m(k) + \max \left\{ -5.0, \min \left\{ \left( \eta \alpha_m(k) + (1-\eta) \beta_m \right) [u_m(k) - u_0(k)], \ 0 \right\} \right\} \]

\[ \bar{u}_m(k) \] – the speed of the saturated traffic section (congestion tail), measured

\[ m_0 \leq m \leq m_h \]

\[ u_0(k) = V_f = 69.0 \text{ [mph]} \]

\[ R_m(k) = \min \left\{ d_m(k), Q_{m,o}, Q_m - \bar{q}_{m-1}(k-1) \right\} \]

\[ q_m(k) = \bar{q}_{m-1}(k-1) + R_m(k) - s_m(k) \]

\[ \alpha_m(k) = H \left( Q_m - q_m(k) \right) \]

\[ \beta_m = H \left( 1/L_{m,o} \right) \]

\[ 0 \leq \eta \leq 1 \]
VSL Design – Balance between Demand and Onramp Length

\[ \sum_{m=1}^{M} \alpha_m(k) = 1 \]
\[ \sum_{m=1}^{M} \beta_m = 1 \]
\[ \sum_{m=1}^{M} (\eta \alpha_m(k) + (1 - \eta) \beta_m) = 1, \quad \eta \geq 0 \] can be chosen based on time-of-day

\[ \beta_m = H(L_m) = \frac{\prod_{\mu=1, \mu \neq m}^{M} L_{\mu}^{2}}{1 \sum_{\mu=1}^{M} L_{\mu}^{2}} = \frac{1}{\sum_{\mu=1}^{M} \frac{1}{L_{\mu}^{2}}} \frac{1}{\sum_{\mu=1, \eta \neq \mu}^{M} \prod_{\eta=1}^{M} L_{\eta}^{2}} \]
\[ \mathbf{L} = [L_1, L_2, ..., L_M] \]

\[ \alpha_m(k) = H(q_m^c(k) - q_m(k)) = \left( \frac{q_m^c(k) - q_m(k)}{\sum_{\mu=1}^{M} (q_{\mu}^c - q_{\mu}(k))^2} \right)^2 \]
VSL Design – Critical VSL Determination

- Determination of $u_0(k)$

$$u_0(k) = \min \{V_f, v_0(k)\}$$

- Determination of $u_M(k)$, a $\rho$-control Approach

$$u_M(k) = u_M(k-1) + \gamma \cdot \min \{(Q_b - \bar{q}_{m-1}(k)), \bar{v}_{M+1}(k) \cdot (\rho_c - \bar{\rho}_{M+1}(k))\}$$

or

$$u_M(k) = u_M(k-1) + \begin{cases} 
\zeta_{\rho_1} \cdot (\rho_c - \rho_{M+1}), & \text{if } \rho_{M+1} < \rho_c \\
\zeta_{\rho_2} \cdot (\rho_c - \rho_{M+1}), & \text{if } \rho_{M+1} > \rho_c 
\end{cases}$$

$$u_M(k) = u_M(k-1) + \begin{cases} 
\zeta_{\rho_1} \cdot (\rho_c - \rho_{M+1}), & \text{if } \rho_{M+1} < \rho_c \\
\zeta_{\rho_2} \cdot (\rho_c - \rho_{M+1}), & \text{if } \rho_{M+1} > \rho_c 
\end{cases}$$
VSL Design – Determine \((V_{st}, \rho_{st}, L_{st})\) for Congested Section

- Depending on the following factors:
  - measured upstream mainline flow
  - flow from onramp or RM rate
  - roadway storage capacity
- \(\rho_{st}\) is specified first
- \(V_{st}(k)\) is then determined by FD relationship and the following

\[
V_{st}(k) \cdot \rho_{st}(k) \geq Q_b \\
\rho_c \leq \rho_{st}(k) \leq \rho_J
\]
VSL Design – Congested Length Estimation

- Using density model for estimation at time $k$

$$\rho_m(k+1) = \rho_m(k) + \frac{T}{L_m \lambda_m} (\lambda_m \rho_{m-1}(k) u_{m-1}(k) - \lambda_m \rho_m(k) u_m(k) + r_m(k) - s_m(k))$$

- If $\rho_m(k) \geq \rho_{st}(k)$, then link $m$ is added to the congested section starting from the link of the critical VSL

$$L_{st}(k) := L_{st}(k-1) + 1$$
VSL Design – Discharge Section Clearing

- Storage capacities of those two sections \( \left( \lambda_{\text{dis}} L_{\text{dis}} + \lambda_b L_b \right) \rho_J \)

\[
\rho_b = \frac{Q_b}{V_b}
\]

- \( V_b, \rho_b \) – the corresponding speed and density to be operated at;
- Assuming a constant discharging flow for the bottleneck 
  \( Q_b \cdot (1 - x\%) \)

- Time needed to recover from congestion density \( \rho_J \) to \( \rho_b \) would be

\[
T_{\text{dis}} = \frac{T_{\text{dis}} \lambda_{\text{dis}} u_M \rho_M + \left( \lambda_{\text{dis}} L_{\text{dis}} + \lambda_b L_b \right) \left( \rho_J - \rho_b \right)}{Q_b \cdot (1 - x\%)}
\]

\[
\Rightarrow T_{\text{dis}} = \frac{\left( \lambda_{\text{dis}} L_{\text{dis}} + \lambda_b L_b \right) \left( \rho_J - \rho_b \right)}{\left( Q_b \cdot (1 - x\%) - \lambda_{\text{dis}} u_M \rho_M \right)}
\]
Method 3: CRM Design

- Based on known VSL for each link
- Assuming driver full compliance at this stage
- Control design method: Model Predictive Control
  - At each time step, predict traffic based on model, initial condition, and boundary condition
  - Design control based on model
  - Feed the first step control back to the system
- Constraints based on empirical estimation of traffic flow drop probability
- Linear objective function: \[ J = TTS - TTD \]
  - Over the predictive time horizon (with on ramp queue, etc)
  - With multiple on/off ramps coordinated
- Math problem: Linear Optimization with Constraints
- Simple and efficient in computation
CRM Design: Model and Constraints

- Assuming VSL Enforced in Control Design, $u_m(k)$ is the designed VSL, known

$$
\rho_m(k+1) = \rho_m(k) + \frac{T}{L_m \lambda_m} \left( \lambda_m \rho_{m-1}(k) u_{m-1}(k) - \lambda_m \rho_m(k) u_m(k) + r_m(k) - s_m(k) \right)
$$

$$
w_m(k+1) = w_m(k) + T \cdot \left[ d_m(k) - r_m(k) \right]
$$

s.t.

$$
0 \leq w_m(k) \leq L_m^{(r)} \cdot \rho_J
$$

$$
0 \leq r_m(k) \leq \min \left\{ d_m(k), Q_{m,o}, \lambda_m \left( Q_m - \bar{Q}_{m-1}(k) \right), \lambda_m u_m(k) \cdot (\rho_J - \bar{\rho}_m(k)) \right\}
$$

$$
\varphi_0(u_m(k)) \leq \rho_m(k) \leq \min \left\{ \rho_J, \varphi(u_m(k)) \right\}
$$

The function $\rho_m = \varphi(u_m)$ corresponds to a selected traffic drop probability contour
CRM Design: Model and Constraints

- In practical implementation, the following is used:

\[ \tilde{u}_m(k) = \min \left\{ u_m(k), \tilde{v}_m(k) \right\} \]

in place of \( u_m(k) \) considering the discrepancy of desired VSL and practically measured speed.
CRM Design: Model and Constraints

- **onramp queue length**
  \[ 0 \leq w_m(k) \leq L_m^{(r)} \cdot \rho_j \]

- **direct constraints on ramp metering rate:**
  - ramp capacity
  - ramp demand
  - ramp-mainline compatibility: mainline space available to onramp in-flow for both free-flow and congested

  \[ 0 \leq r_m(k) \leq \min \{ d_m(k), Q_{m,o}, \lambda_m(Q_m - \bar{q}_{m-1}(k)), \lambda_m u_m(k) \cdot (\rho_j - \bar{\rho}_m(k)) \} \]

\( \lambda_m \approx 2 \sim 3 \) since only 3 lanes are affected in practice
Direct Constraints on Ramp Meter Rate

- The following two terms are all flows in unit and they all describe the remainder space in mainline. In non-congested situation, either of them could be the candidate; in congested situation, the measured flow $\bar{q}_{m-1}(k)$ will be very low, the first term tend to be big, while the second term tend to be small since density is close to the jammed density and speed is low; therefore the second term is likely to be candidate;

$$
\lambda_m \left( q_m^c - \bar{q}_{m-1}(k) \right), \lambda_m \tilde{u}_m(k) \cdot (\rho_J - \bar{\rho}_m(k))
$$

- Because only the spaces of the 2 nearside lanes could be practically used for onramp merging vehicles, the lane number here should be practically

$$
\lambda_m = 1.5 \sim 2.0
$$

Instead of the practical lane number of that link
CRM Design: Model and Constraints

- **Mainline density constraints** – from the traffic dynamics viewpoint
  - mainline compatibility: mainline space available to upstream traffic
  - feasible speed and density

\[
\varphi_0(u_m(k)) \leq \rho_m(k) \leq \min\{\rho_j, \varphi(u_m(k))\}
\]
Constraints: How to Determine Upper Bound of Feasibility Set

- **CTM:** Desired speed and density restricted on a triangular FD

\[
q(k) = \begin{cases} 
\min \{v_f \rho(k), Q_c, v_f \left( \rho_j(k) - \bar{\rho}(k) \right) \}, & \bar{\rho} \leq \rho_c \\
\min \{v_f \rho(k), Q_c, w \left( \rho_j(k) - \bar{\rho}(k) \right) \}, & \bar{\rho} > \rho_c 
\end{cases}
\]

- **METANET:** Desired speed and density restricted on FD Curve

\[
V(\rho_i(k)) = V_f \exp \left( -\frac{1}{a} \left( \frac{\rho_i(k)}{\rho_c} \right)^a \right)
\]

- **Traffic Drop Probability Contour:** Feasible region is an area bounded by the contour and 2 straight-lines \( v = V_f; \ \rho = \rho_j \)
  - More relaxed constraints
  - Less likely infeasibility in optimization process
Upper Bound from Empirical Traffic Drop Probability Analysis
Upper Bound from Empirical Traffic Drop Probability Analysis

Density (vpm) vs. Speed (mph) graph showing flow contours.

Flow contours:
- 2000
- 1500
- 1000
A Selected Contour Can Be Fit with a 3rd Polynomial

- Another way is to curve-fit the traffic drop probability contour in the following form

\[
\bar{\rho}_m = c_m^{(3)} \cdot \bar{u}_m^3 + c_m^{(2)} \bar{u}_m^2 + c_m^{(1)} \bar{u}_m + c_m^{(0)}
\]

Then the constraint becomes:

\[
\rho_m (k) \leq \min \left\{ \rho_J, c_m^{(3)} \cdot \tilde{u}_m^3 (k) + c_m^{(2)} \tilde{u}_m^2 (k) + c_m^{(1)} \tilde{u}_m (k) + c_m^{(0)} \right\}
\]

which does not need linearization.
Lower Boundary of Feasible Set in $v - \rho$ Plane

- To determine lower bound

$$\phi_0(v) \leq \rho$$

- $\phi_0(v)$ the lower bound of the envelop of the traffic data on the $\rho - v$ plane, which could be curve-fitted with 2$^{nd}$ or 3$^{rd}$ order polynomials;
Example of Envelop in \( \nu - \rho \) Plane
Equivalent Envelop in $q - \rho$ Plane
Equivalent Envelop in $q - \rho$ Plane with Box Plot
Simplified Feasible Region for Optimization

- Since the traffic drop probability contour is somehow close to the flow-contour, we could use the following simplified constraint:

\[ \varphi_0(v) \leq \rho_m(k) \leq \min\{\rho_J, Q_{m,op} / \tilde{u}_m(k)\} \]

- \(Q_{m,op}\) the expected operational capacity – slightly lower than the maximum observed flow;
CRM Design: Model and Constraints

Therefore the following constraints are used for preliminary implementation. We need to compare with the linearized traffic drop probability contour. The physical meaning is clear from operation point of view:

\[ 0 \leq w_m(k) \leq L_m^{(r)} \cdot \rho_J \]
\[ 0 \leq r_m(k) \leq \min \{ d_m(k), Q_{m,o}, \lambda_m(q_m^c - q_{m-1}(k)), \lambda_m \tilde{u}_m(k) \cdot (\rho_J - \bar{\rho}_m(k)) \} \]
\[ \varphi_0(v) \leq \rho_m(k) \leq \min \{ \rho_J, Q_m^{op} / \tilde{u}_m(k) \} \]
\[ \tilde{u}_m(k) = \min \{ u_m(k), \bar{v}_m(k) \} \]
**CRM Design:** Model Based Predictive Control over \( N_p \)

- **Assuming VSL Enforced in Control Design:**

\[
\begin{align*}
\rho_m (k + j) &= \rho_m (k + j - 1) + \frac{T}{L_m \lambda_m} \left( \lambda_m \rho_{m-1} (k + j - 1) u_{m-1} (k) - \lambda_m \rho_m (k + j - 1) u_m (k) + r_m (k) - s_m (k) \right) \\
w_m (k + j) &= w_m (k + j - 1) + T \cdot \left[ d_m (k) - r_m (k) \right] \\
s.t. \\
0 &\leq w_m (k + j) \leq L_m^{(r)} \cdot \rho_j \\
0 &\leq r_m (k + j) \leq \min \left\{ d_m (k + j), Q_{m, o}, \lambda_m (q^e_m - \bar{q}_{m-1} (k + j)), \lambda_m \tilde{u}_m (k) \cdot (\rho_j - \bar{\rho}_m (k + j)) \right\} \\
\varphi_0 (\nu) &\leq \rho_m (k + j) \leq \min \left\{ \rho_j, Q_{m, op} / \tilde{u}_m (k) \right\} \\
\tilde{u}_m (k) &= \min \left\{ u_m (k), \bar{v}_m (k) \right\} \\
j &= 1, ..., N_p
\end{align*}
\]
CRM Design: Optimization Problem Formulation for CRM

\[ J = TTS - TTD \]

\[
\begin{align*}
\min_{Z} & \\
\text{s.t.} & \\
AZ & \leq b \\
A_{eq}Z & = b_{eq} \\
b_l & \leq Z \leq b_u \\
Z & = \left[ r_1(k+1), \ldots, r_1(k+N_p), \ldots, r_M(k+1), \ldots, r_M(k+N_p) \right]^T
\end{align*}
\]

\[ 0 \leq w_m(k + j) \leq L_m^{(r)} \cdot \rho_j \]

\[ 0 \leq r_m(k + j) \leq \min \left\{ d_m(k + j), Q_{m,o}, \lambda_m \left( q_m^c - \overline{q}_{m-1}(k + j) \right), \lambda_m \tilde{u}_m(k) \cdot \left( \rho_j - \overline{\rho}_m(k + j) \right) \right\} \]

\[ \varphi_0(v) \leq \rho_m(k + j) \leq \min \left\{ \rho_j, Q_m^{op} / \tilde{u}_m(k) \right\} \]

\[ \tilde{u}_m(k) = \min \left\{ u_m(k), \overline{v}_m(k) \right\} \]

\[ j = 1, \ldots, N_p \]
CRM Design: Performance Measure for Bottleneck Flow Maximization

\[ TTS = T \sum_{j=1}^{N_p} \sum_{m=1}^{M} L_m \lambda_m \rho_m (k + j) + \]  \hspace{1cm} (TTT)

\[ T \sum_{j=1}^{N_p} \sum_{o} w_o (k + j) \]  \hspace{1cm} (time due to onramp queue)

\[ TTD = \alpha_{TTD,0} T \sum_{j=1}^{N_p} \sum_{m=1}^{M-1} \lambda_m L_m q_m (k + j) + \alpha_{TTD,M} T \sum_{j=1}^{N_p} \lambda_m L_m q_M (k + j) \]

\[ \alpha_{TTD,M} \gg \alpha_{TTD,0} > 0 \]
**CRM Design: Performance Measure for Bottleneck Flow Maximization**

- **Why choosing trade off between TTT and TTD**
  - The system is not independent – it has interaction with arterials
  - Arterials are not in the model – TTD is included to represents ts interests
  - We may have to allow more vehicles to move into freeway to avoid arterial grid-lock
  - The bottleneck-flow maximization would allow freeway to have a storage intersection although the performance may be degraded somehow
Macroscopic Simulation

- Preliminary macroscopic traffic simulation has been done
- 1 minute aggregated BHL data; each data set has 24 hours data
- Uncertainties to onramp and off-ramp up to 40% randomly
- CMR rate: Onramp queue length taken into account – if onramp limit reached, deactivate RM
- Onramp capacity 880 veh/hr
- Jammed density 230 veh/mile
Macroscopic Simulation – Scenario Runs

Each dataset is a BHL day of 1-minute sample data which are used as initial and boundary conditions for the macroscopic model in simulation.

| Strategy | Dataset 1 |  | Dataset 2 |  | Dataset 3 |  | Dataset 4 |  | Average |  |
|----------|-----------|  |-----------|  |-----------|  |-----------|  |----------|  |
|          | TTS %     |  | TTD %     |  | TTS %     |  | TTD %     |  | TTS %    |  | TTD %    |
| CRM      | -10.2     |  | + 4.5     |  | -13.1     |  | + 4.7     |  | -9.7     |  | + 4.4    |  | -10.5    |  | + 5.2    |  | -10.9    |  | + 4.7    |
| VSL      | -13.9     |  | + 6.5     |  | -16.7     |  | + 6.8     |  | -13.6    |  | + 6.2    |  | -13.2    |  | + 7.0    |  | -14.4    |  | + 6.6    |
| CRM + VSL| -13.9     |  | + 6.3     |  | -16.8     |  | + 6.8     |  | -13.6    |  | + 6.2    |  | -13.6    |  | + 7.0    |  | -14.5    |  | + 6.6    |
Integrated Traffic Control Simulation Platform (ITCSP)

Data aggregation: micro to macro

Macroscopic model

Macroscopic control design

Desired CRM rate

Desired VSL

Driver acceptance & behavior factor

Driver acceptance & behavior factor

Onramp metering

VSL Sign or on-vehicle feedback

Microscopic traffic model of road network for simulation
ITCSP

- Aimsun default microscopic model
- PATH developed NGSIM oversaturated flow microscopic model (Hwasoo Yeo):
  - Vehicle following, acceleration/deceleration
  - Lane changing
  - Merging from on ramp
  - Departure from off-ramp
  - Multiple vehicle types taken into account including heavy trucks
- Sensor measure and control calculation update time step 20s
- Feedback (VSL & CRM) update time step: 1 min
ITCSP

- **Site Modeled:**
  - I-80 W from Carlson to I-580 E & I-880 S split
  - 7 links with on-ramps and off-ramps about 6.5 miles
  - HOV lane ignored
- **AM Peak:**
  - Main bottleneck is Bay Bridge Toll Plaza and the capacity limit of Bay Bridge
  - Demand is far beyond capacity of Bay Bridge; Control cannot help much; VSL could be used to harmonize traffic
- **PM Peak:**
  - Main bottleneck is I-80W at I-580 E & I-880 S split
  - Control to maximize bottleneck flow
Example – I-80W PM Peak
ITCSP – I-80 W PM Peak

- **Flow distribution ratio at the split:** 60% to I-580 E & I-880 S; 40% to I-80 W
- **Demands** (generated from a simplified and modified OD Table of DKS Model for I80W ICM) are the same with different random seeds for simulation scenario runs
  - Status quo (no control)
  - VSL only *(all times; fuzzy logic switching)*
  - CRM only with onramp queue override *(all times; fuzzy logic switching)*
  - Combination of VSL and CRM *(all times; fuzzy logic switching)*
Fuzzy Logic Switching on/off Control

IF: $v_M(k-1) < V_{on}$ or $v_{M+1}(k-1) < V_{on}$ or $o_M(k-1) > O_{on}$ or $o_{M+1}(k-1) > O_{on}$

Then: Control is ON

IF: Control is ON for certain time period and

IF: $v_{M+1}(k-1) > V_{off}$ and $o_{M+1}(k-1) < O_{off}$

THEN: Control is OFF
ITCSP – I-80 W PM Peak

- **Vehicle types:** 95% passenger cars; 5% HDT
- **Driver compliance ratio to VSL:** 100% for all the control scenarios; and 30% for VSL all times
- **Driver compliance ratio to RM:** almost 100%
- **Performance parameters for evaluation**
  - Accumulated flow over time
  - Total Time Spent, TTS (including mainline and onramps, virtual onramps – spillback to arterials)
  - Total Travel Distance, TTD (only makes sense in congested situation)
  - Total Delay
ITCSP – I-80 W PM Peak

- **Simulation results show:** performance comparison for different control scenarios
Accumulated Demand

Accumulated Demand of Most Upstream Mainline and Each Onramp Including I-593, Tangent is the Demand Flow.
Total Time Spent (including onramp queue and spillback to arterials)
Total Travel Distance
Total Delay

The graph illustrates the total delay over time for various traffic control strategies. The y-axis represents the delay in seconds, ranging from 0 to 8000, and the x-axis represents time in seconds, ranging from 0 to 18000. Different lines correspond to different control strategies:

- Blue line: no control
- Pink line: all time VSL
- Green line: all time combined
- Cyan line: switched VSL
- Pink line: switched combined
- Black line: switched monitoring
- Green line: all time VSL 90% compliance

As time increases, the delay for each strategy also increases, with the no control strategy having the highest delay compared to others.
Next Steps: Completion of Analysis and Modeling in Current Project This Year

- Refine macroscopic simulation for Methods 1 & 3
- Refine ITCSP model:
  - (a) extend to a longer stretch of I-80W;
  - (b) use the full O-D table;
  - (c) evaluate different control strategies;
  - (d) evaluate different ratios of driver compliance;
  - (e) develop control strategies for multiple bottlenecks;
- Implement Method 3 in TOPL
Next Steps: Limited-Scale Testing in Current Project This Year

- Traffic Impacts of Lower-Speed Compliant Vehicle:
  - Implement VSL from Method 3 as set speed for Cooperative ACC test vehicle using real-time traffic data along a stretch on I-80W and measure its interactions with surrounding traffic using BHL video tracking

- Driver Acceptance:
  - Display VSL from Method 3 as *advisory speed* in a Cooperative ACC test car along I-80 W and survey reactions of naïve drivers from the general public to this type of speed limit and record the *actual* ACC set speeds that they select

- Need real-time traffic condition data feed from D4 TMC to do these tests
Next Steps: Additional Work Needed Towards Deployment

- **Field Testing:**
  - Identify promising locations for testing in CA and evaluate them in simulation
  - Use a freeway stretch equipped with detectors to test VSL advisories
    - *How best to display VSL information to all drivers within reasonable time and expense, without needing CTCDC review and approval?*
  - Test Coordinated Ramp Metering strategy along a corridor already equipped with ramp metering
  - Test combined VSL and CRM along a freeway stretch with ramp meters
  - Test combined VSL & CRM on I-80W using VSL signs planned for I-80 ICM project (at later stage)

- **Develop coordination between freeway ramp metering and arterial signal control for system optimization**