Variable Speed Advisory/Limit and Coordinated Ramp Metering for Freeway Traffic Control

Project Meeting
Caltrans DRI

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Outline

- Approaches for Traffic Management
- Active Traffic Management
- Progressive Project Plan for 4 Years
- Our Approaches – Combined VSL & CRM
- Implementation Related Issues
- Why Traffic Speed Estimation Required?
- Performance Parameters
- Site Selection Consideration
- VSM Feedback to Drivers
- Discussion
Approaches in Traffic Handling

Solving Freeway Traffic Problems: congestion, safety, emission, …

Road expansion

Cost fund limit

Land use limit in urban area

ATM for cost effective and maximum use of the system

Demand manage

Mainline flow manage

Incident/accident manage

Traveler’s information

Ramp metering

Speed harmonization & limit, Traffic signs, RM, HOV/HOT, ATMS

Mode choice

Onramp flow

Mainline traffic flow largely determined by driver behavior

Mainline traffic flow will be affected or controlled

Routing, accident removal
Active Traffic Management

- Overall Picture
- Combined VSL and CRM – Backbone of ATM
- International and US Practices
- International VSL Practices
- VSL Practices in US
- Summary of Performance of VSL
Combined VSL & CRM - Backbone of ATM

- Pre-Trip planning & mode use selection
  - Traffic assignment for individual veh. routing
  - Demand Management
    - Combined VSL & CRM for integrated mainstream and arterial traffic control
    - Bottleneck detection and management
    - Capacity Management
      - Traffic Control Assistance Measures
        - Driver advice or mandate on: lane use limit; merge/lane-change assistance/limit; dynamic shoulder use; dynamic use of HOV/HOT lane; gap advice
International and US Practices

- FHWA Scan of ATM Practices in Denmark, England, Germany, and The Netherlands (2010)
  - Increase in average throughput for congested periods of 3 to 7 percent;
  - Increase in overall capacity of 3 to 22 percent;
  - Decrease in primary incidents of 3 to 30 percent;
  - Decrease in secondary incidents of 40 to 50 percent;
  - Overall harmonization of speeds during congested periods;
  - Decreased headways and more uniform driver behavior;
  - Increase in trip reliability; and
  - Ability to delay onset of freeway breakdown
International and US Practices

- US Traffic Management Strategies
  - Ramp Metering
  - Lane Management (or Managed Lane)
  - VSL and Managed Lanes \textit{(WSDOT)}
  - Shoulder Use (TOD, Transit)
  - Pricing (HOT)
  - Traveler Information
International and US Practices

- European Traffic Management Strategies (England, The Netherlands, New Zealand, Australia, …)
  - Speed Harmonization/Lane Control
  - Queue Warning
  - Dynamic Use of Hard Shoulder
  - Junction Control
  - Dynamic Re-routing
  - Traveler Information for pre-trip and in-route decisions
  - Coordinated Ramp Metering (HERO in Australia)
  - VSL (UK, the Netherlands, …)
## International VSL Practices

<table>
<thead>
<tr>
<th>VSL location</th>
<th>Regulation</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>M25 (London), M42 (Birmingham), UK</td>
<td>Enforcement</td>
<td>Safety, Reduce recurrent congestion</td>
</tr>
<tr>
<td>A3, A5 and A8, Germany</td>
<td>Enforcement</td>
<td>Stabilize traffic flow</td>
</tr>
<tr>
<td>E18, Finland</td>
<td>Advisory</td>
<td>Harmonization speed</td>
</tr>
<tr>
<td>the Netherlands</td>
<td>Mandatory</td>
<td>Safety, congestion warning</td>
</tr>
<tr>
<td>the Netherlands</td>
<td>Mandatory</td>
<td>Safety in adverse weather conditions</td>
</tr>
<tr>
<td>E4 motorway, Stockholm, Sweden</td>
<td>Advisory</td>
<td>reduce shockwave; improve safety and throughput</td>
</tr>
<tr>
<td>A56, 3-lane urban motorway, Naples, Italy</td>
<td>Enforcement</td>
<td>Improve safety, throughput, and emission reduction</td>
</tr>
<tr>
<td>A7/E15 south of Lyon, France</td>
<td>Advisory</td>
<td>Improve mobility and safety</td>
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VSL Practices in the U. S.

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</thead>
<tbody>
<tr>
<td>MD 100, Maryland</td>
<td>Advisory</td>
<td>Reduce recurrent congestion</td>
</tr>
<tr>
<td>I-35W, Twin Cities, Minnesota</td>
<td>Advisory</td>
<td>Prevent shock waves propagation</td>
</tr>
<tr>
<td>I-270/I255 Corridor, Missouri</td>
<td>Advisory</td>
<td>Solve congestion problem</td>
</tr>
<tr>
<td>I-80 in Wyoming</td>
<td>Enforcement</td>
<td>Adverse weather conditions increase throughput, reduce collision in adverse weather</td>
</tr>
<tr>
<td>I-5, I-90, Washington</td>
<td>Enforcement</td>
<td>Safety, winter weather and road conditions</td>
</tr>
<tr>
<td>I-40, New Mexico</td>
<td>Enforcement</td>
<td>Reduce rear-end and lane-change crash</td>
</tr>
<tr>
<td>I-4, Florida</td>
<td>Advisory</td>
<td></td>
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</tbody>
</table>
VSL Study and Practices – Summary of Performance

- Speed harmonization: reduced speed different between lanes and over time
- Reduced shock waves at congestion start
- More significant for safety improvement: in UK, 25~40% accident reduction observed
- Throughput increased at some locations
- Higher speed achieved for congested density at some locations
- Achieved delay of traffic break down
- Compliance rate varies from countries to countries for advisory
- VSL enforcement is significantly more effective than advisory
VSL Study and Practices – **Summary of Algorithms**

- Implementation objectives were more safety related than mobility improvement
- Dynamically changing speed limit signs to adjust to changing roadway conditions, oftentimes weather related
- Algorithms are ad hoc, local instead of system wide
- Not for bottleneck flow maximization
- Speed harmonization can reduce shockwave, but not necessarily able to improve bottleneck flow
- Most VSL algorithms used in practice were only half of our algorithm: reduce shockwave at congestion tail
- Bottleneck flow maximization was missed
Our Approach

- Control Strategy
- Control Objectives and Benefits
- Bottleneck Flow Maximization
- Shockwave Reduction/Avoidance
- Other Traffic Aspects Taken Into Consideration
- Overall System Structure
Control Strategy

- Combined VSL and CRM
- CRM for Onramp Demand Control
- VSL for Mainline Flow Control
  - Maximize Bottleneck Flow
  - Remove/reduce Shockwave
- Applicable to Recurrent Freeway Bottleneck with
  - Lane reduction bottleneck
  - Waving Effect with Virtual Lane Drop (freeway split)
Example – I-80 W in PM Peak
Control Objectives and Benefits

- Control Objectives:
  - Maximize bottleneck flow
  - Delay congestion start time if possible
  - Control density distribution
  - Achieve higher density (thus flow) for the same speed
  - Reduce total congestion time
  - Reduce shockwaves, including Stop & Go
  - Avoid off-ramp blocking and spill-back
  - Minimize VHT and Maximize VMT system wide
  - Byproduct: Improve safety and emissions
Control Objectives and Benefits

- **Coordinated Ramp Metering (CRM)**
  - Control density (or average density immediately downstream of the onramp) (mobility)
  - Balance demand and capacity at each onramp along the stretch, taking into account queue length limit (mobility & equity)

- **Benefits of CRM: Mitigating Local RM Problems**
  - Conflict with mainline flow which could aggravate the congestion at bottlenecks in peak hours
  - Storage capacity of onramps may not be fully used due to the demand flow and the length differences between onramps
  - Significant negative impact to traffic on arterials
Control Objectives and Benefits

- **Variable Speed Limits (VSL)**
  - Influence driver behavior \(\Rightarrow\) reduce speed variance in the same lane and between lanes (safety and environment)
  - Avoid shock waves (mobility, safety and environment) \(\Rightarrow\) to avoid primary and secondary collisions
  - Keep homogenous flow when density changes (mobility) \(\Rightarrow\) same speed can be maintained for higher density
  - Smooth traffic when demands are too high, or RM has to be switched off due to ramp length limit (equity, mobility)

- **VSL and CRM are complementary in function**
  - RM only controls the demand into the freeway; it has to be switched off if demand from local streets is too high
  - VSL affects the mainline driver behavior (traffic flow)
  - Enforced VSL could help regulate the flow as desired to maximize the bottleneck flow
Bottleneck Flow Maximization

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

Answer: Feeding flow into the bottleneck is low – even if the speed in the bottleneck is increasing, the density is decreasing.
Bottleneck Flow Maximization

- Control strategy: to maximize bottleneck flow;
- Applicable bottleneck type: (virtual) lane drop and weaving
- How: (1) create a discharge section before the bottleneck; (2) regulate the discharge section flow to bottleneck capacity flow
- Example: flow of 3-lane discharge section could be made closer to (a 2-lane) bottleneck capacity flow
VSL Algorithm

- Stage 1: Congestion Start

- Stage 2: Congestion back propagate upstream
  - Strategy 1
  - Strategy 2

- Another Critical Point:
  - To determine the Critical VSL $u_M$ according to measured discharge section flow, density or occupancy such that the flow is close to bottleneck capacity flow.
SnapShot of VSL Strategy 1: at Stage 1

$L_M = L_{m_h} = L_{m_t}$

$u_0 = V_f$

$V_d$
Snapshot of VSL Strategy 1 at Stage 2

- $L_M = L_{m_h}$
- $L_{m_t}$
- $L_m$
- $L_0$

Bottleneck

$V_d$

$V_c$

$u_0 = V_f$

$VSL_t$

$VSL_h$

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Snapshot of VSL Strategy 2: Gradually Increasing to $u_M$
Other Traffic Aspects Taken Into Consideration

- The following factors have been taken into account:
  - Driver acceptance
    - Limit on speed variation over time
    - Limit on speed variation over space
  - Demand and capacity of onramp and mainline
  - Onramp storage capacity and estimated queue length
  - Maximizing the feeding flow to the bottleneck
  - Addressing possibility of creating queue upstream
Overall System Structure

- CRM Stand Alone
- Combine VSL & CRM
CRM Stand Alone for Freeway Corridor Traffic Control

PATH Control Computer

TMC Computer

RM Rate

RT data

Cabinet 1
- 2070 Controller

Cabinet 2
- 2070 Controller

Cabinet 3
- 2070 Controller

Cabinet N
- 2070 Controller

Traffic detector
Combined VSL & CRM for Freeway Corridor Traffic Control

- PATH Control Computer 2
- PATH Control Computer
- TMC Computer
- Wireless 3G modem or Internet
- 3G modem
- RM traffic data
- RM Rate
- Cabinet 1
  - 2070 Controller
  - Onsite Server Computer
- Cabinet 2
  - 2070 Controller
- Cabinet 3
  - 2070 Controller
- Cabinet N
  - 2070 Controller
- Traffic detector
- Combined VSL & CRM for Freeway Corridor Traffic Control
- RM traffic data
- RM Rate
- Speed 35 For Max Flow
Combined VSL & CRM for Freeway Corridor Traffic Control
CRM Stand Alone for Freeway Corridor Traffic Control

TMC Computer

Cabinet 1
170/2070 Controller

Cabinet 2
170/2070 Controller

Cabinet 3
170/2070 Controller

Cabinet N
170/2070 Controller

Traffic detector
Progressive Project Plan for 4 Years

- Phase 1: Preparations for Field Testing of Combined VSL & CRM
- Phase 2: Field Experiment of CRM
- Phase 3: Field Experiment of VSL
- Phase 4: Field Test Combining VSL & CRM
Phase 1: Preparations for Field Testing of Combined VSL & CRM (15 Months)

- Objectives:
  - To prepare for future field testing of Variable Speed Advisory (VSL) and Coordinated Ramp Metering (CRM).

- SOW:
  - Finalize site selection criteria and select proper site
  - Extensive literature review on VSL and CRM
  - Preparations for control computers and VMS at RFS
  - Define performance parameters for evaluation
  - Data collection and modeling of selected site
  - Validation of the VSL and CRM algorithms with simulation for the selected site
  - Preparations for use of 30 s real-time data from PeMS for supporting later stage tests
  - Preparing final report
Phase 2: Field Experiment of CRM (12 Months)

- **Objectives:**
  - Determine the technical feasibility, implement coordinated CRM and evaluate its effectiveness in improving corridor traffic flow.

- **SOW:**
  - Refine traffic state parameter estimation
  - Calibrate and refine traffic simulation for selected site
  - PATH computer to
    - interface with the TMC host computer
    - get real-time traffic data
    - send generated RM rate for selected freeway corridor
  - Evaluate effectiveness of CRM algorithm
  - Write Phase 2 report to document findings
Phase 3: Field Experiment of VSL (12 Months)

- **Objectives:**
  - Implement and test VSL at selected site for traffic flow and safety improvement

- **SOW:**
  - Retrieve real-time 30 s data from Caltrans PeMS
  - Use a PATH computer to control the display of VSL on portable VMS
  - Progressively switch on VSL displays for short time periods
  - Modify algorithms and tune the system based on observed effects on traffic flow and driver compliance
  - Collect data before and after VSL and analyze data for performance evaluation
  - Write Phase 3 report describing results
Phase 4: Field Test Combining VSL and CRM (12 Months)

- Objectives:
  - Test combined VSL & CRM and evaluate effectiveness

- SOW:
  - Improve algorithms based on previous tests
  - Implement combined VSL & CRM for selected site
  - Collect data before/after the control system activation
  - Systematic test of the combined algorithm
  - Analyze the data for evaluation of the performance
  - Assess merits and limitations of control algorithms, leading to implementation recommendations
  - Prepare Final Report to document all findings and recommendations
Implementation Related Issues

- VSL and CRM can be implemented independently
- When implementing CRM alone, the speed in the model just uses the real time estimated traffic speed
- Critical to the success of field test → Data Health
- Traffic state parameter estimation based on RT data
- Proper feedback to the driver for better acceptance
  - Good visibility and advance in time/location
  - Appropriate location of VMS
  - Simple message to avoid driver distraction
  - VMS message update at a reasonable frequency
  - Convincing reason to adopt the advised speed
Implementation Related Issues

- Critical Factors for VSL Implementation
  - Higher level control logics for switch VSL according to the traffic
    - Demand below bottleneck capacity
    - Demand close to bottleneck capacity
    - Demand over bottleneck capacity
  - Road geometry and bottleneck type
    - lane reduction or virtual lane reduction
    - Weaving
    - Upstream storage section
  - VSL advisory using portable VMS
  - Suitable advisory messages and VMS locations
  - Traffic state parameter estimation (data health)
Implementation Related Issues

- Critical factors for implementation of CRM
  - Higher level control logics for switch CRM according to the traffic
    - Demand below bottleneck capacity
    - Demand close to bottleneck capacity
    - Demand over bottleneck capacity
  - Ramp storage capacity and demand: long enough to store most vehicles from arterials ➔ no need to coordinate with arterials
  - Onramp queue detection to improve performance
  - Traffic state parameter estimation (data health)
    - Non-model based
    - Model based
Implementation Related Issues

- Critical factors for implementation of CRM
  - Most situations impossible due to
    - High demands
    - Uneven distribution of demands
    - Road geometry limit
  - Coordination with arterial traffic control would be necessary
    - If road geometry permit
      - Traffic signal control in favor of certain movements in peak hours
      - Routing using VMS
  - An example of necessity for coordination
Why is Speed Estimation Required?

- HERO (also ALINEA) project recommended measurements downstream of onramp to determine RM rate instead of upstream
Why is Speed Estimation Required?

Measure $q_{in}$ to determine $q_{r}$
Outcome at bottleneck is not measured $q_{cap}$
This method results in very poor operations
Why is Speed Estimation Required?

Measure $q_{cap}$ to determine $q_r$
Outcome at bottleneck is measured $q_{cap}$
This method results in good operations

\[ \text{Diagram:} \quad q_{r} \quad \checkmark \quad q_{in} \quad q_{cap} \]
Why is Speed Estimation Required?

Measure $q_{\text{cap}}$ to determine $q_{\text{r}}$
Outcome at bottleneck is measured $q_{\text{cap}}$
This method results in good operations
Why is Speed Estimation Required?

- Reasons: measurements downstream of onramp can
  - Include flow rate from onramp
  - Account sooner for congestion back-propagation
  - Measurements upstream do not offer those advantages in-time
Why is Speed Estimation Required?

- **Benefits with traffic speed estimation**
  - Simple first order model (CTM) can be linearized
  - Linearized model for traffic flow estimation and prediction along the corridor at any point, in principle, due to speed availability
  - Sensor located upstream or downstream of the onramp does not matter much for CRM
  - Sensor spacing can be flexible: 200 ft ~ 700 ft
  - Avoid infrastructure changes: maximally use current infrastructure for VSL and CRM to optimize traffic flow to the extent possible
- It is also required for VSL control
Why is Speed Estimation Required?

- Speed estimation using loop detectors
  - Single loop gives vehicle count and occupancy
  - From Occupancy to speed, one needs vehicle length;
  - From 30 s aggregated g-factor method using assumed vehicle length (which is usually fixed)
    ➜ speed estimation is bad in traffic transition phases and in congestion
Why is Speed Estimation Required?

- Speed estimation using loop detectors
  - Dual loop direct speed estimation needs event (60 Hz) data; dual loop aggregated (over 30 s) does not offer much advantage, only redundancy;
  - Speed estimation using single loop event data can have similar accuracy as from dual loop event data;
Performance Parameters – VSL Only

- Traffic demand (from arterials)
- Onramp (freeway practically accommodated) flow
- Bottleneck flow
- TTT
- TTD
- Average journey times and variability in
- Speed limit compliance
- Average speed profiles
- Average speed/flow relationship (driver behavior change)
- Lane utilization (lane flow)
- Speed less than X
- Speed differential over-time and between lanes
- Shockwave propagation distance at congestion start
- Crash times over certain period of time
Performance Parameters – CRM Only

- TTT
- TTD
- Onramp demand/queue
- Ramp metering rate and onramp flow (into freeway)
- Impact on arterials traffic
- Mainline flow
Performance Parameters – Combined VSL & CRM

- TTT
- TTD
- Onramp queue and impact on arterial intersections
- Bottleneck flow
- Speed differential over-time and between lanes
- Shockwave propagation time/distance at congestion start
- Crash times over certain period of time
Site Selection Consideration

- Site Selection Criteria
- Some Candidate Sites
  - I-880 Nimiz Freeway South of Mrina
  - SR99-Mack Road:
    - NB AM
    - SB PM: Lane Reduction Bottleneck
  - SR51- Exposition Blvd:
    - SB PM: Lane Reduction Bottleneck
Site Selection Consideration - Criteria

- Mainly for CRM
  - Road geometry and traffic situation
  - Onramps are close enough; otherwise not need for coordination
  - All onramps are metered along the corridor, otherwise, the one without meter will cause problems
  - Mainline sensor density is adequate
  - Onramp flow & queue detection is critical to CRM
  - Avoiding off-ramp blockage and spill-back
  - Hardware setup would allow CRM control (D4 TMC)
  - Coordinate with arterial if road geometry permit
    - Routing with VMS
    - Traffic signal control
Site Selection Consideration - Criteria

- Mainly for VSL
  - Traffic demand is high to over-saturated in peak hours
  - The corridor has a recurrent bottleneck downstream
  - The most downstream (main) bottleneck has the minimum capacity or largest v/c ratio
  - Congestion cause is lane reduction or virtual lane reduction
  - Upstream of the main bottleneck has adequate storage section without off-ramp or has a separated off-lane
  - Detection at critical locations:
    - at the start of the bottleneck and 500 m upstream;
    - each section has detectors 300~500 m apart;
    - sensor health is important for good performance
VSM Feedback: Speed Harmonization Netherland
VSM Feedback: Dynamic Speed Limits in Randstad, Germany
VSM Feedback: Side-Mount Congestion Warning Icon, Germany
VSM Feedback: VSL and Hard Shoulder Use, UK
VSM Feedback: VSL and Queue Warning
VSM Feedback: VSL and Hard Shoulder Use, M42
VSM Feedback: Suggested VMS for Feedback

Speed 35
For Max Flow

Speed 35
Congestion Ahead