Freeway Recurrent Bottleneck Flow Maximization with VSA/VSL and CRM

Xiao-Yun Lu: Research Engineer
Danjue Chen: Post-doctoral Researcher
Steven Shladover: Research Engineer

California PATH Program, U. C. Berkeley
November 7, 2012
Outline

- VSL Study and Practice
- Bottleneck Flow Maximization
- Relationship with SPECIALIST
- Application to Other Freeway Bottlenecks
- Site Selection Considerations
- California Site Selection Examples
- Summary
VSL Study and Practice

- **Safety Benefits:**
  - Reduced speed difference between successive vehicles, between lanes and over time
  - Reduced shock waves at congestion start
  - More significant for safety improvement: in UK, 25~40% accident reduction observed

- **Mobility Benefit**
  - Throughput increased at some locations
  - Higher speed achieved for congested density at some locations
  - Achieved delay of traffic breakdown

- Higher compliance rate will be more effective ➔ Enforcement may be necessary
VSL Study and Practice

- Control Approaches:
  - Implementation objectives were more safety and weather related
  - Dynamically changing speed limit signs to adjust to changing roadway conditions
  - Some algorithms were ad hoc, local instead of system wide; some advanced algorithms simulated and tested, but performance was not satisfactory
  - VSL algorithms used in practice
    - Some for reducing shockwave at congestion tail
    - Some for flow maximization
Bottleneck Flow Maximization

- Control Strategy
- Control Objectives and Benefits
- Bottleneck Flow Maximization Strategy
- Shockwave Reduction/Avoidance
- Other Traffic Aspects Taken Into Consideration
- Implementation Related Issues
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 Bottlenecks with
  - Lane reduction bottleneck
  - Weaving section with virtual lane drop (freeway split)
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
  - Byproducts: Improve safety and emissions
Control Objectives and Benefits

• Variable Speed Limits (VSL)
  – Influence driver behavior ➔ reduce speed variance in the same lane and between lanes (safety and environment)
  – Avoid shock waves (mobility, safety and environment) ➔ to avoid primary and secondary collisions
  – Keep homogenous flow when density changes (mobility) ➔ 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 in CA
  – VSL affects the mainline driver behavior (traffic flow)
  – Enforced VSL could help regulate the flow as desired to maximize the bottleneck flow
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
  - Avoiding negative impact to arterial traffic
Bottleneck Flow Maximization Strategy

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 Strategy

How: (1) create a discharge section before the bottleneck;
(2) regulate the discharge section flow to bottleneck capacity flow
VSL Algorithm

- Stage 1: Congestion Start

- Stage 2: Congestion back propagation upstream

- 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 (one typical vehicle speed) 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

\[ L_M = L_m \]

\[ L_m \]

\[ L_0 \]

\[ u_0 = V_f \]

\[ u_M \]

\[ V_c \]

\[ V_d \]
Snapshot of VSL Strategy 2: Gradually Increasing to $u_M$

Bottleneck

$L_M$

$L_{m_h}$

$L_m$

$L_{m_f}$

$L_0$

$V_f$

$V_c$

$V_{SL_t}$

$V_{SL_h}$

$V_d$

$u_M$
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
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 or deployment → Data Health
- Traffic state parameter estimation based on real time 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 switching 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 section
    - Freeway merge
  - VSL advisory using portable VMS
  - Suitable advisory messages and VMS locations
  - Sensor location and traffic state estimation
Implementation Related Issues

• Critical factors for implementation of CRM
  – Higher level control logics for switching 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
  – Sensor location limit ➢ needs traffic state estimation
Implementation Related Issues

- Critical factors for implementation of CRM
  - Most situations are difficult due to
    - High demands
    - Uneven distribution of demands over time and space
    - Road geometry limits
  - Coordination with arterial traffic control would be necessary
    - If road geometry permits
      - Traffic signal control in favor of certain movements in peak hours
      - Routing using VMS
Incorporate with SPECIALIST

- Those two algorithms address different freeway traffic problems, but complementary to each other
- Bottleneck Flow Maximization:
  - Recurrent bottleneck flow maximization (even if upstream demand is very high)
  - Shockwave reduction/avoidance at the end of the queue
  - Speed smoothing in other cases
- Current SPECIALIST algorithm
  - To resolve moving jam
  - To improving traffic flow
Incorporate with SPECIALIST

A macroscopic version of SPECIALIST could be used to

- If demand upstream is not very high – no more than the downstream capacity, use SPECIALIST for
  - fine tuning the VSL upstream of the queue to remove any moving jam
  - stabilizing the traffic further upstream to avoid potential of moving jam

- If demand upstream is very high (a created congestion section is unavoidable):
  - reduce shockwave effects at the end of the queue
    - fine tuning the flow moving into the storage section if queue wave-front estimation is available
Application to Other Freeway Bottlenecks

- **Lane Reduction**
  - Mainline lane reduction
  - Onramp acceleration lane ends
- **Virtual Lane Reduction**
  - Weaving/merging at freeway diverge
- **Freeway Merge**
  - With lane reduction
  - Without lane reduction
Lane Reduction due to Acceleration Lane Ends

Reccurrent bottleneck due to Merge lane end
Virtual Lane Reduction

- Freeway Diverge due to
  - Unbalanced Split Ratio
  - Weaving/Merging Effect

Example – I-80 W in PM Peak
Freeway Merge – **with Lane Reduction**

- **Road Geometry**

  \[ Q_1 + Q_2 \geq Q_\delta; \quad q_1(t) + q_2(t) < Q_\delta \]

- **Congestion cause:** physical capacity drop, weaving/merging effects
Freeway Merge – with Lane Reduction

- Control Strategy:

  Freeway Merge with Lane Reduction:

  \[ Q_1 + Q_2 \geq Q_b; \quad q_1^{clr} + q_2^{clr} \approx \alpha_w Q_b, \]

  \[ 0 < \alpha_w \leq 1, \text{ site dependent weaving factor to be tuned} \]

- Objective: to produce the joint flow close to bottleneck capacity flow; to minimize friction
Freeway Merge – without Lane Reduction

- Road Geometry: Congestion may be caused by weaving effect

\[ Q_1 + Q_2 \approx Q_b; \quad q_1(t) + q_2(t) < Q_b \]

- Congestion cause: weaving/merging effects
Freeway Merge – **without Lane Reduction**

- **Control Strategy**

  \[ Q_1 + Q_2 \approx Q_b; \quad q_1^{ctr}(t) + q_2^{ctr}(t) \approx \alpha_w Q_b \]
  
  \(0 < \alpha_w \leq 1\), site dependent weaving factor to be tuned

- **Objective:** to produce the joint flow close to bottleneck capacity flow; to minimize friction
Freeway Merge

- Define *weighted demand index* for each freeway branch based on the following factors
  - All the demand (traffic volume) on each freeway section upstream of the merge
  - All storage capacities: onramps, off-ramps and upstream storage section (for VSL)
  - Affected freeway section lengths determined by historical traffic data and observations

- Balance of flows from two freeways branches upstream according to weighted demand index

- Direct generalization to the merge of more than two freeways
Site Selection Considerations

- Mainly for VSL
  - Traffic Condition
    - Traffic demand is high in peak hours
    - Recurrent bottleneck most downstream
    - Congestion caused by lane reduction, *virtual lane reduction*, or freeway merge
  - Geometry
    - Upstream of the *main bottleneck* has adequate storage
    - No off-ramp or with a protected off-lane
  - Detection and data at critical locations:
    - at the start of the bottleneck and 500 m upstream;
    - each section has detectors 300~500 m apart;
    - Data quality is critical for performance
Site Selection Considerations

- Mainly for CRM
  - Road Geometry and Traffic Situation
    - Traffic is medium to high, but not saturated
    - Onramps are close enough
  - Facility
    - All onramps are metered along the corridor
    - Mainline sensor density is adequate
    - Onramp flow & queue detection is critical to CRM
    - Hardware setup would allow CRM control
  - Coordinate with arterial if road geometry permits through
    - Routing with VMS
    - Traffic signal control
Site Selection Considerations

- **Approach**
  - Road geometry analysis
  - Macroscopic traffic data analysis based on PeMS
  - Individual traffic detector data analysis to find causes of congestion
  - Discussion with local traffic engineers
  - Site visit for direct observation/experience of traffic conditions
California Site Selection Examples

- Some Candidate Sites
  - I-880 Nimitz Freeway Near Auto Mall Parkway
    - NB PM
  - SR99-Mack Road (Caltrans D3 - Sacramento):
    - NB AM: Lane Reduction Bottleneck
I-880 Nimitz Freeway NB AM Near Auto Mall Parkway
I-880 Nimitz Freeway NB AM Near Auto Mall Parkway

I-880 NB near Auto Mall Parkway, Fremont

Data Analysis Section

BN3

BN2
9/17/2012

MP: 15.07 -> 16.6
9/17 – 9/19

Occupancy

Speed
SR99-Mack Road NB AM Traffic
SR99-Mack Road NB AM Traffic

SR99-Mack Road, NB, Road Geometry and Sensor Location/Health

moderate congestion

Mp295.3 -297.1

On-Ramps:
- Fruitridge Road
- 47th Ave
- Florin Road
SR99-Mack Road NB AM Traffic
7/11/2012 – 7/13/2012

MP: 295.3 -> 296.5 -> 297.1

Occupancy

Speed
Summary

- VSL and CRM are complementary in function for freeway traffic management
- Combined VSL and CRM can be used for recurrent bottleneck flow maximization
- Simulation did before showed benefits in TTT and TTD
- VSL feedback to individual vehicle through I2V for advising or used as set-speed for ACC/CACC vehicles
- Generalization to freeway network is underway – will be simulated; could possibly be tested in FHWA STOL project, and Caltrans project at SR99 merge with SR50
- PATH will test CRM first at two sites: Caltrans D4 and D3; later VSL could be tested (still working on institutional issues)
- SPECILIST could be combined with bottleneck flow maximization method to improve overall performance in different traffic situations
VSL Feedback: Suggested VMS Displays for Feedback

- Speed 35 For Max Flow
- Speed 35 Congestion Ahead