



Variable Speed Limit and Coordinated Ramp Metering

TOPL Meeting
10/09/08





Outlines

- **VSL Practice Study**
- **Simulation for Combined of VSL and Ramp Metering**





Part I

Effects of Variable Speed Limits on Motorway Traffic

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87th *TRB Annual Meeting*, Jan. 14-18, 2008





VSL – Papageorgiou et al: Introduction

- **VSL implemented EU was primarily for safety, and less for traffic and environment improvement**
 - Reduce speed variation
 - Fixed ad hoc strategy used in most cases
 - Not much control design for improving traffic throughput
- **Objectives of the paper:**
 - To investigate VSL impact on aggregate traffic flow behavior: flow-occupancy diagram (equivalent to FD flow-density diagram)
 - For enhance of VSL strategy in the future to improve traffic on
 - **Throughput or travel time**
 - **Safety**
 - **Environment**





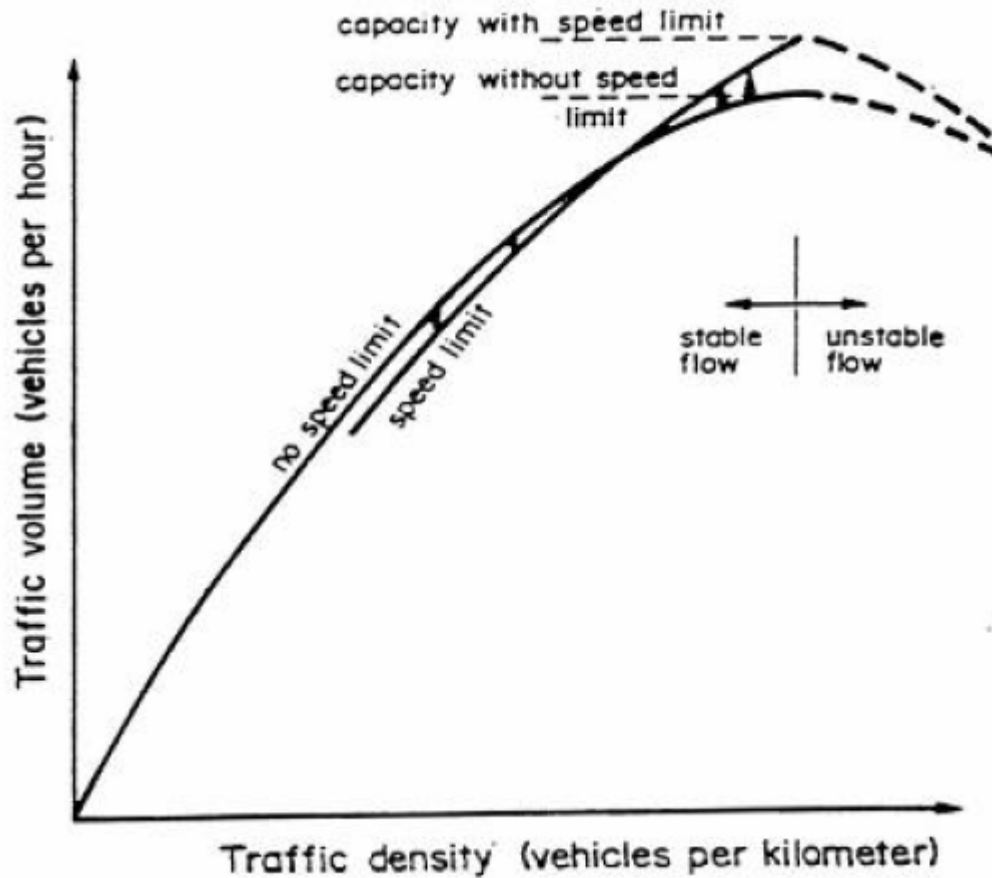
VSL – Papageorgiou et al: Introduction

- **VSL Site data: UK M42**
- **Control strategy:**
 - Rule based algorithm depending on flow, occupancy and speed targeted for safety improvement
 - Open loop time based manual control
 - Not designed for traffic flow optimization → one could not expect much improvement on traffic flow
- **Feedback strategy**
 - Apply speed limit upstream at under critical density to delay congestion onset downstream
 - VMS, advisory
 - NSL, 60mph, 50mph, 40mph



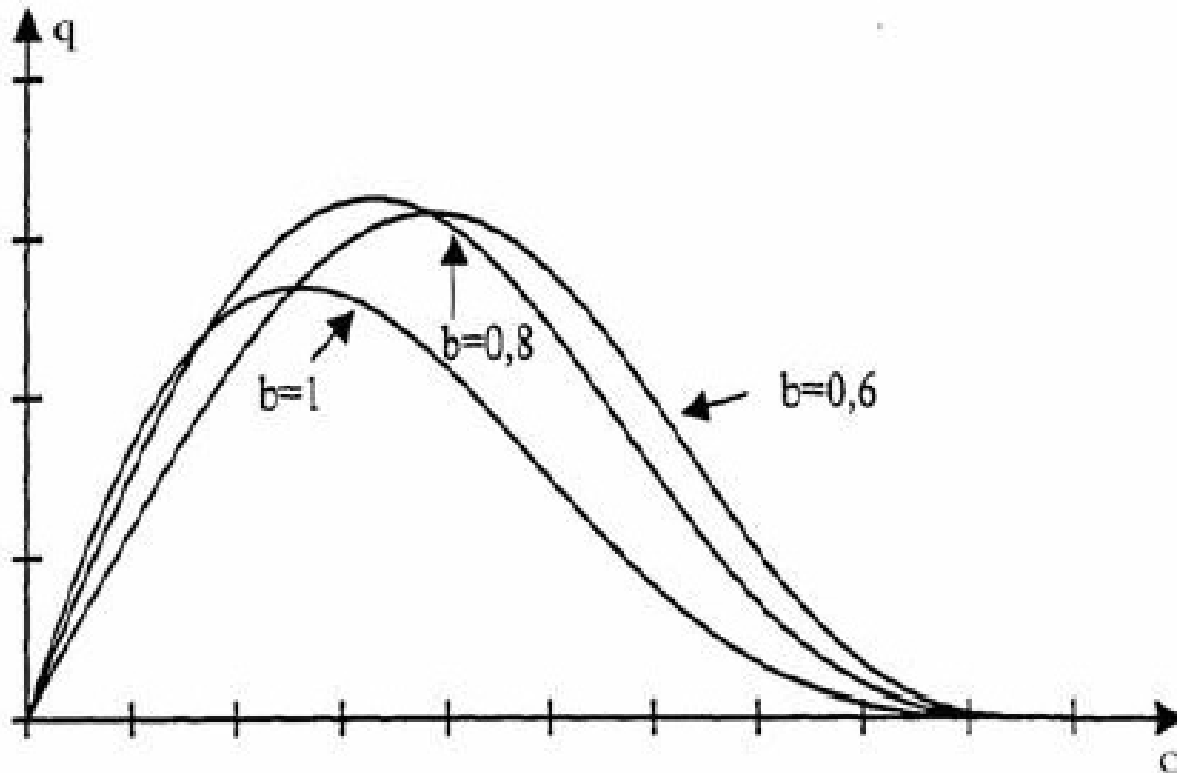
VSL – Papageorgiou et al: VSL Impact on FD

- Zaker (1991)



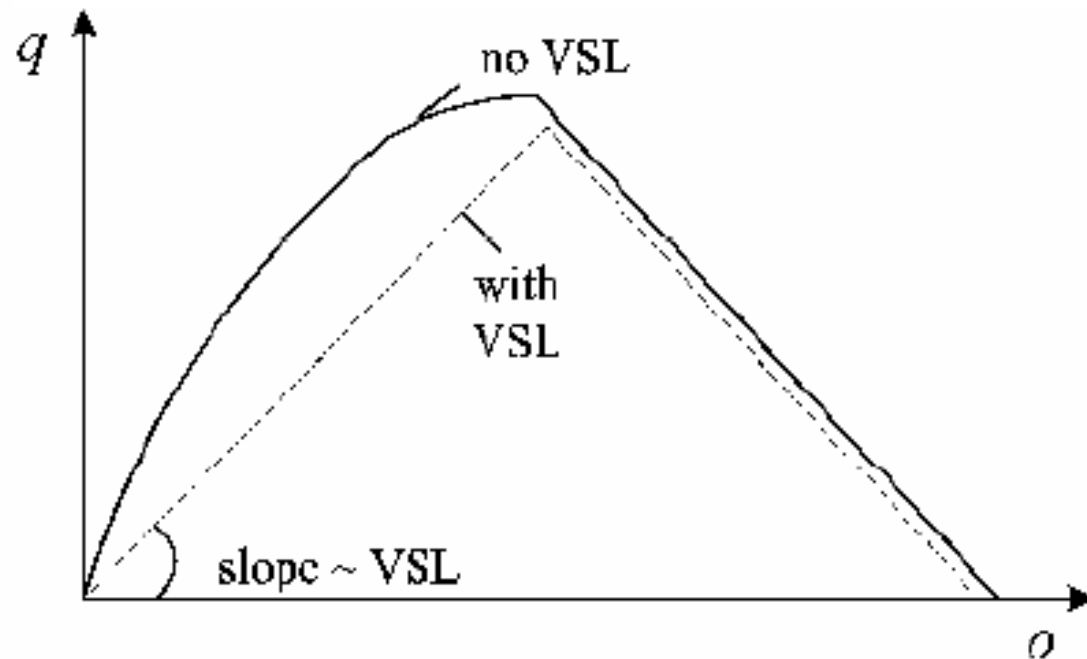
VSL – Papageorgiou et al: VSL Impact on FD

- **Cremer (1979)** b is the ratio between V_{limit} and v_f
- **VSL implemented with advisory; other report did show capacity increase;**



VSL – Papageorgiou et al: VSL Impact on FD

- Hegyi (2004):





VSL – Papageorgiou et al: Summary of Previous Work on VSL

- **Reduce mean speed at under-critical occupancy results in**
 - Same flow with higher occupancy
 - Speed reduction → increase travel time
 - Such a strategy upstream the bottleneck could reduce the accumulation at bottleneck and delay the congestion onset;
- **Reduce mean speed at over-critical occupancy results in increasing throughput and delaying congestion**
 - The two FDs crossing around the critical density or capacity flow





VSL – Papageorgiou et al: Summary of Previous Work on VSL

- **Critical Problems:**
 - Where is the cross point w. r. t. the non-VSL critical occupancy?
 - Are VSL-induced critical occupancy higher than non-VSL counterpart?
 - Are VSL-induced flows higher at over-critical occupancies than the non-VSL counterparts?
 - Is there flow-capacity increase for VSL





VSL – Papageorgiou et al:

- **Methodology for data analysis**

- Aggregated data: (a) over *all* 27 days; (b) over *clear* and *rainy* days;
- Curve fitting to obtain FD
- FD can be flow-density relationship or flow-occupancy relationship;
- This analysis choose the latter based on
 - Occupancy and density are equivalent if average vehicle length is known
 - Occupancy is less sensitive to vehicle length variation
 - Occupancy is directly obtained from loop sensor while density is difficult to estimate
 - Occupancy is less sensitive than density with respect to weather and lighting conditions





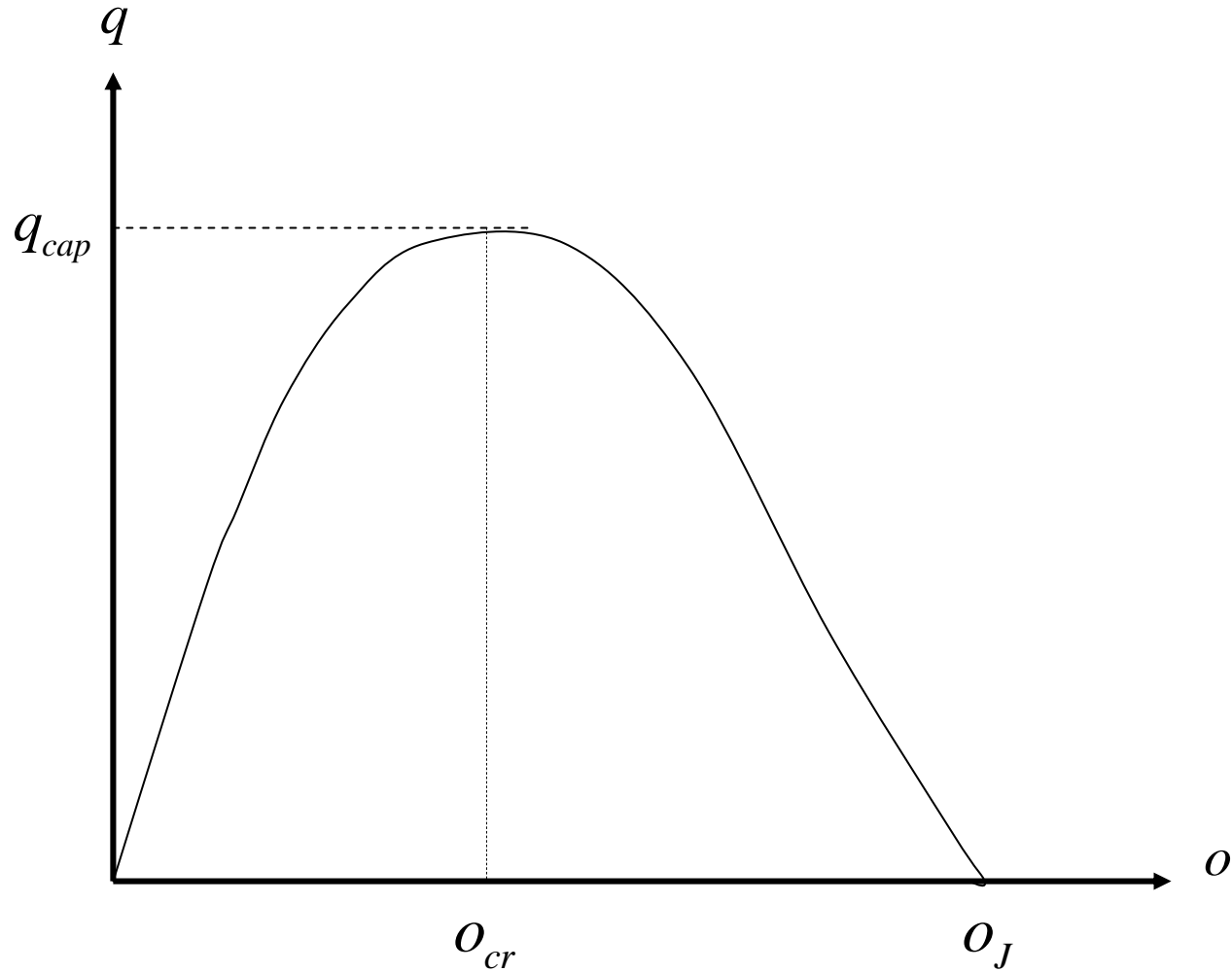
VSL – Papageorgiou et al:

- **Data source**
 - Both direction of M42 freeway (3 lanes each side);
 - Loop detection, stations 500m apart
 - Providing point measured occupancy, flow and speeds;
 - Implemented in 2005 (May-Oct); fine tuned in 2006(Jan-May); both data used;
 - Randomly selected 27 days and classified according to
 - **Weather**
 - **Peak or off-peak hours**
 - Only effective data used; faulty data discarded; no data cleansing/correction/imputation conducted;
 - Weekends and incident also removed;





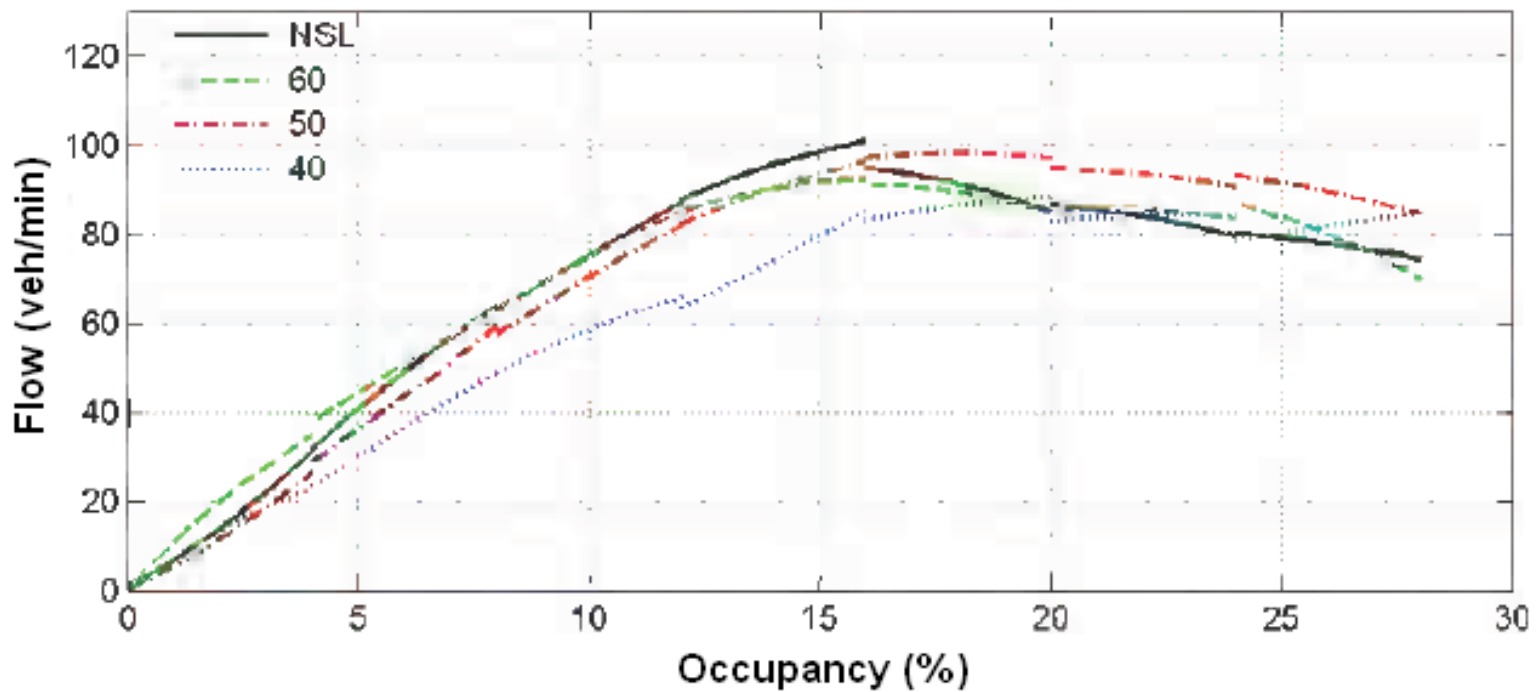
VSL – Papageorgiou et al: Typical Flow-Occupancy Diagram





VSL – Papageorgiou et al: Cross Point for Location 441A

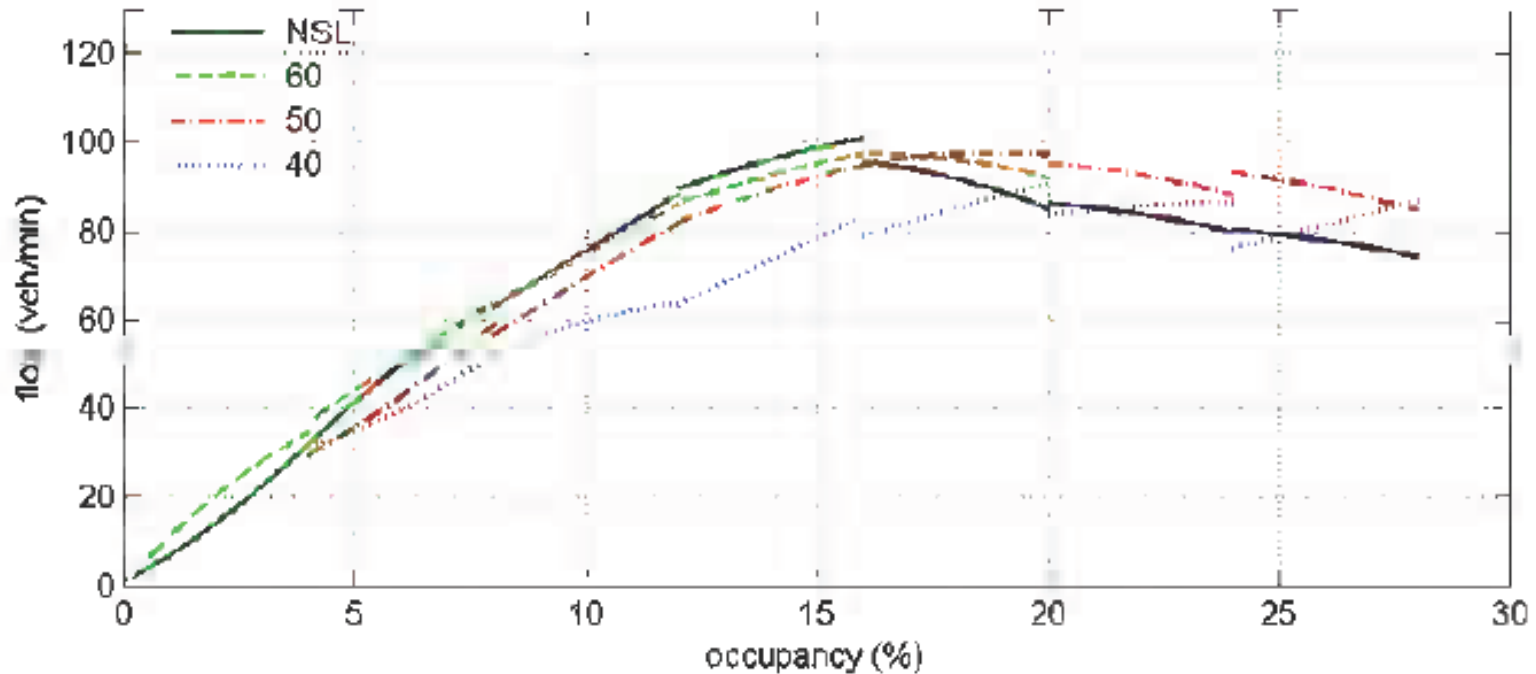
27 representative Days





VSL – Papageorgiou et al: Cross Point for Location 441A

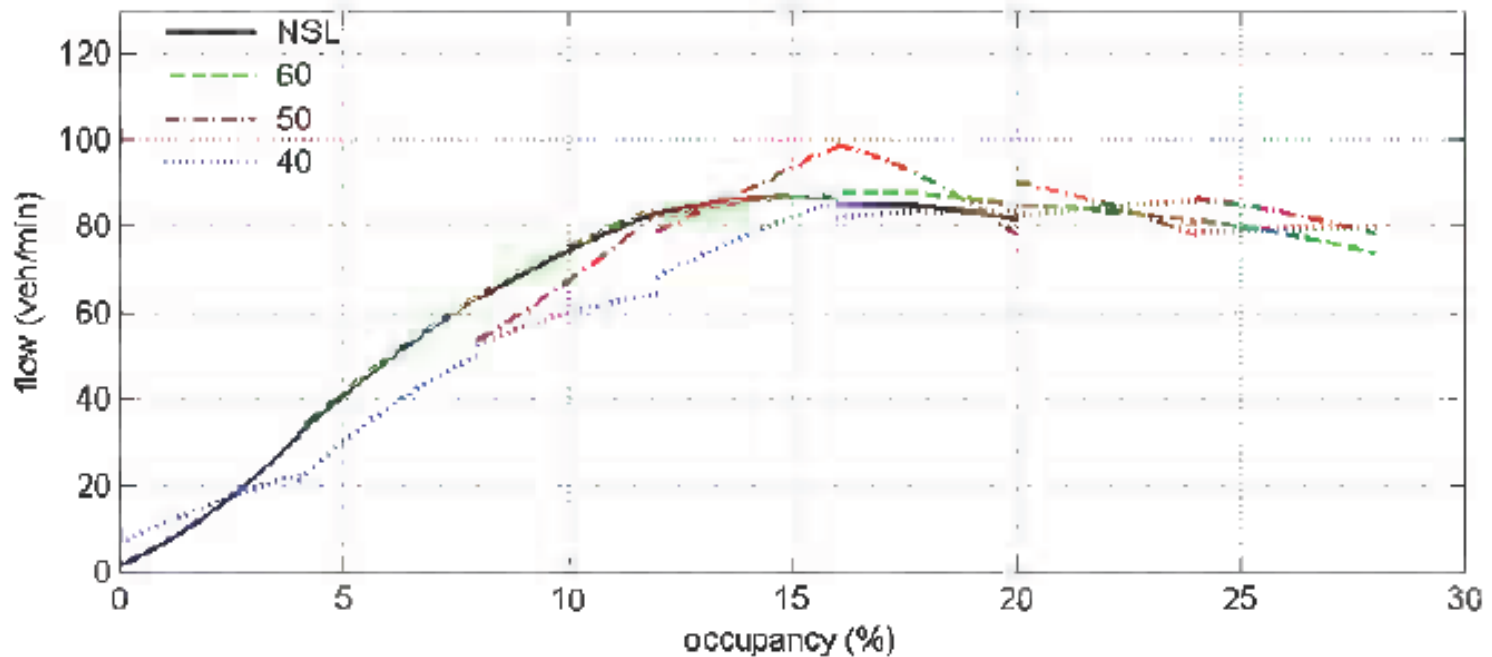
Clear Days





VSL – Papageorgiou et al: Cross Point for Location 441A

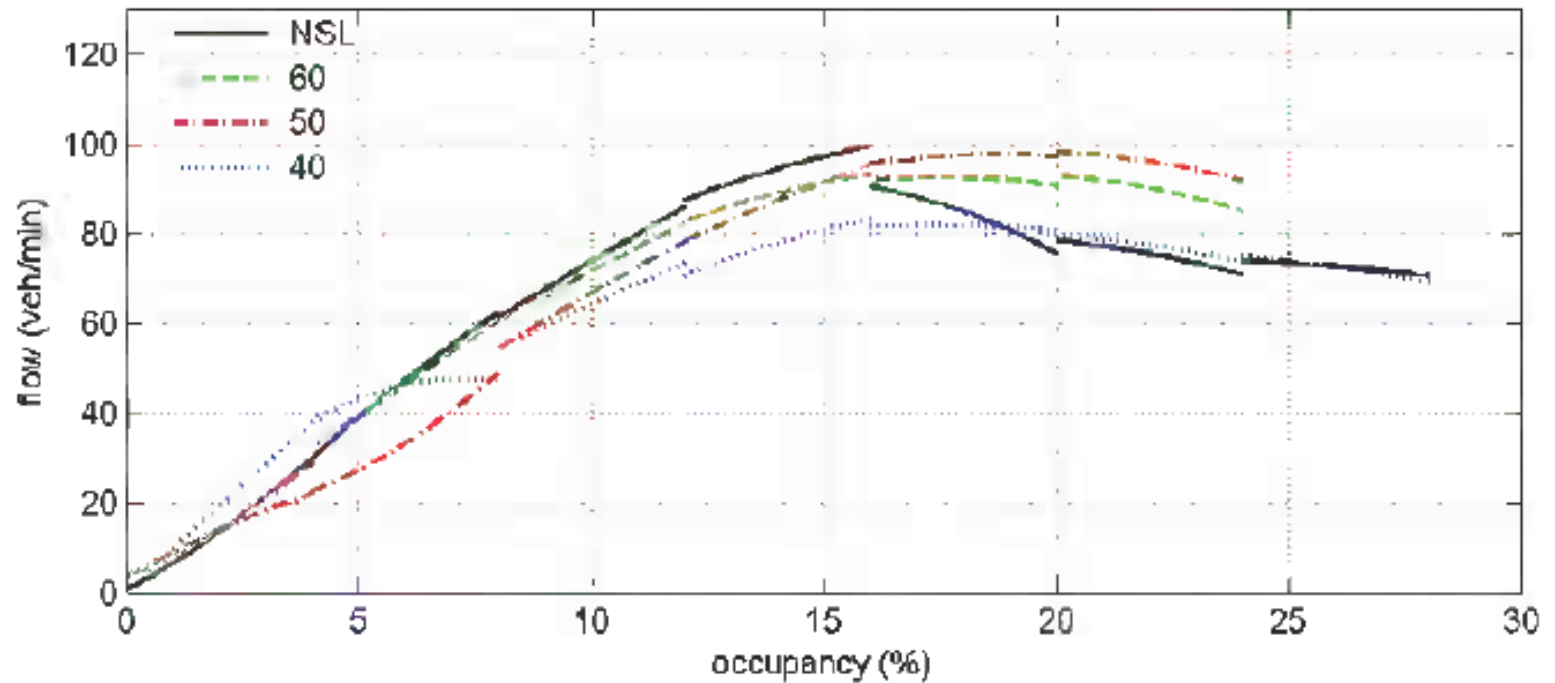
Rainy Days





VSL – Papageorgiou et al: Cross Point for Location 402A

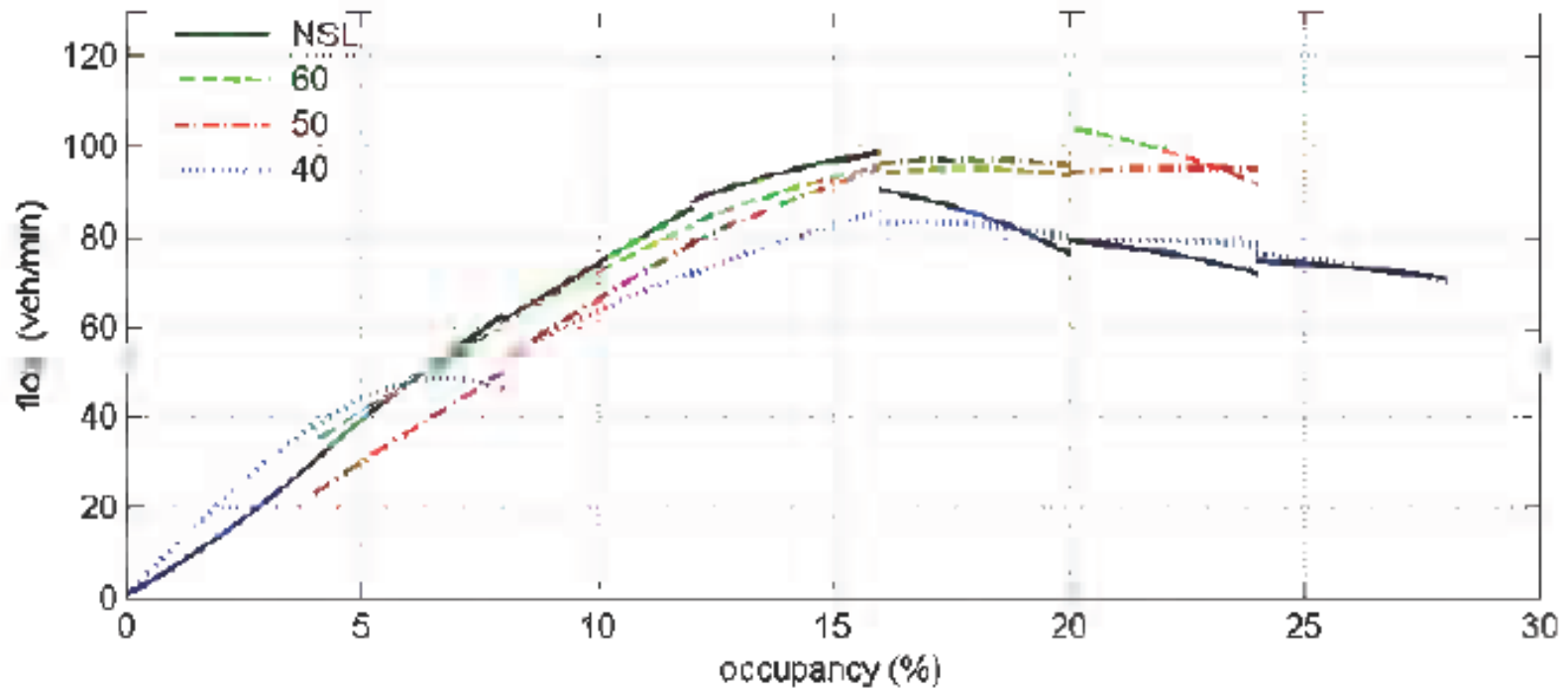
27 representative Days





VSL – Papageorgiou et al: Cross Point for Location 441A

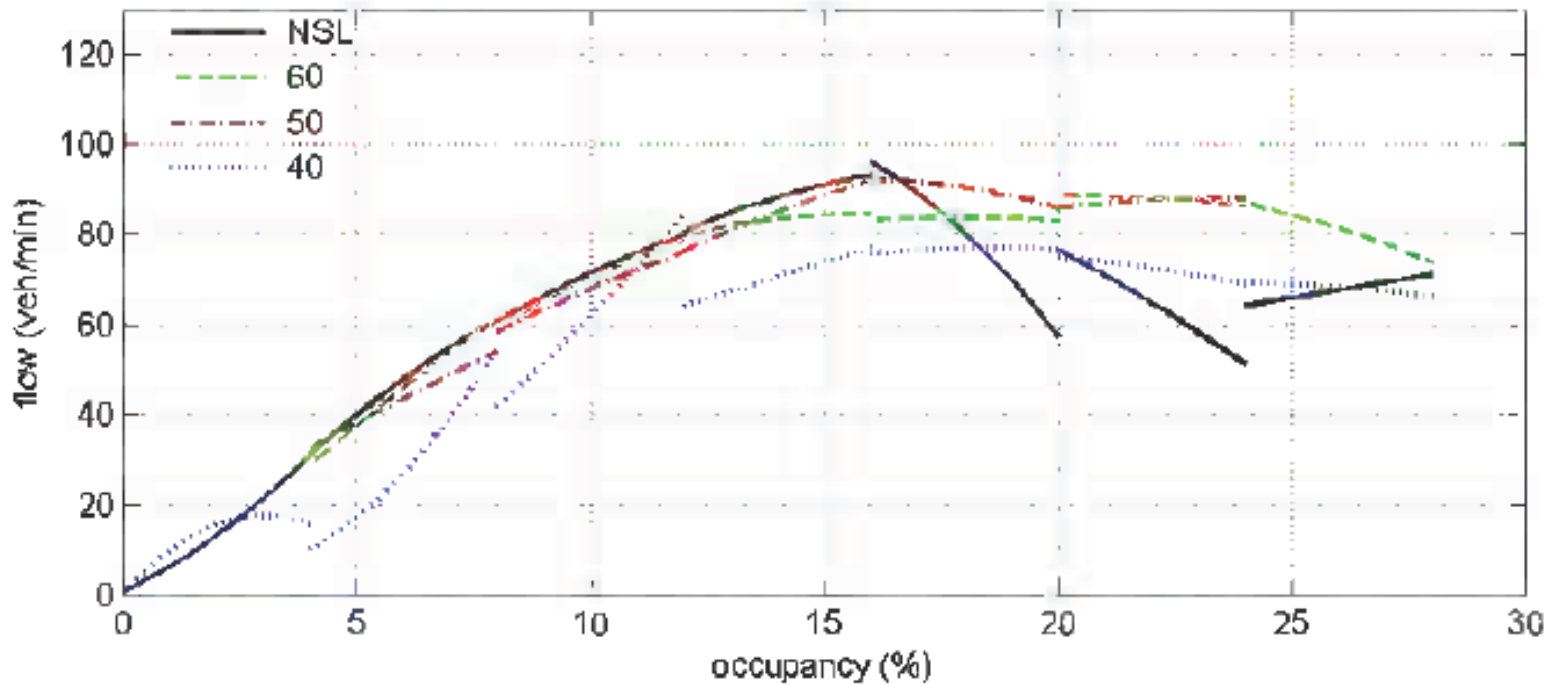
Clear Days





VSL – Papageorgiou et al: Cross Point for Location 441A

Rainy Days





VSL – Papageorgiou et al: Cross Point

- **Reducing Mean Speed at Under-critical Occupancies →**
 - Considering upstream only (locally)
 - Occupancy increasing
 - Speed decreasing
 - May increase travel times → deteriorate traffic flow efficiency
 - Considering a stretch of fwy upstream of bottleneck (semi-globally)
 - Delay bottleneck activation
 - Delay congestion building up
- **The cross-points (if any) characteristics:**
 - lie at increasing occupancy values for decreasing VSL due to the decreasing slope of the under-critical VSL-affected curves;
 - may be no cross-point for very low VSL.





VSL – Papageorgiou et al: Cross Point

- **Cross-points of NSL FD and FD with VSL from data analysis:**
 - VSL=60 → not significant for both clear and rainy days
 - VSL=50, 40 → significant on both clear and rainy days
 - *Critical occupancy* increased: 15%(NVSL) → 20%(VSL)
 - *Corresponding flow* increased
 - **Conclusion:** control efficiency improved
 - Impact on *Capacity* is visible for some but not for others; reasons unclear yet





VSL – Papageorgiou et al: Data Analysis Result

- **Results**

- reduced mean speed at under-critical conditions
- homogenization of speeds (reduced speed variation): relative distance/speed/acceleration
- decrease the slope of the flow-occupancy diagram at under-critical conditions: shift the critical occupancy to higher values;
- enable higher flows at the same occupancy values in overcritical conditions.





VSL – Papageorgiou et al: Rule Based VSL

- **Global rules for efficient switching of VSL:**
 - **(a) VSL-activation at occupancies lower than the cross-point of the VSL and non-VSL flow-occupancy diagrams decreases the traffic flow efficiency (increases travel times), unless it is used to address a downstream bottleneck.**
 - **(b) VSL-activation at the cross-point occupancy or (the latest) at the non-VSL critical occupancy is likely to improve the traffic flow efficiency due to avoidance or delay of congestion as well as improved traffic flow stability which might allow for higher flows under overcritical occupancies.**





VSL – Papageorgiou et al: Rule Based VSL

- **Suggested implementation techniques:**

- For single VSL Control: switch on at critical density improves traffic, but a thresholds to be chosen judiciously;
- Proper selection of thresholds based on measured occupancy, flow, and speed;
- Avoiding switching oscillation considering the response delay of traffic;
- Activation at proper time – not too early nor too late;
- Thresholds variable from location to location:
 - Needs elaborate calibration
 - Location-specific cross-points of the various flow-occupancy curves
- For corridor operation, optimal coordination for those switches/thresholds are necessary;





VSL – Papageorgiou et al: Rule Based VSL

- **Our Comments:**

- For fully evaluate the impact of VSL on traffic flow, the VSL should be judicially designed and feedback to the driver for advisory and/or enforcement;
- The practical data used was some simple rule-based VSL, which does not mean that other VSL control strategy would produce similar results;
- Speed Control should be tightly coupled with Ramp Metering since mean speed and average density are naturally coupled, which should not be separated in control design and synthesis;





Part II

Integrated Ramp Metering and Variable Speed Limit Control of Motorway Traffic Flow

Papamichail, K. Kampitaki, M. Papageorgiou and A. Messmer

2008





Papamichail et al: Introduction

- **Formulated as a discrete optimal control problem with second order dynamics;**
- **Efficient algorithm feasible for large scale systems;**
- **Traffic flow significantly improved with combined VSL and Ramp Metering;**
- **Ramp metering along may be limited by:**
 - Equity issues along a corridor
 - Onramp queue length limit
 - Estimation of density
 - Control delays
- **Main Functions of VLS:**
 - Reduce mean speed under critical density
 - Reduce speed variation: homogenization of flow
 - Reduce mean speed variation between different lanes





Papamichail et al. Introduction

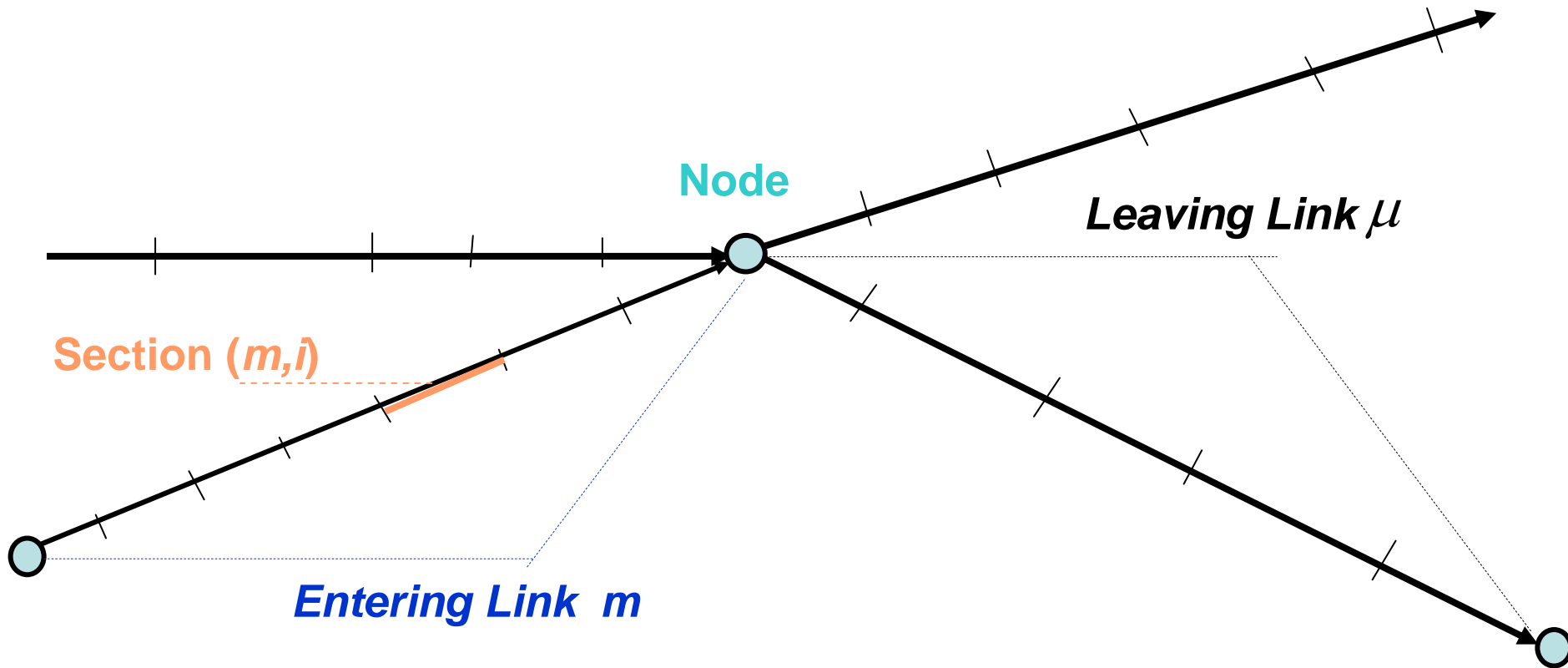
- **Valuation of VSL in the past:**
 - **Safety related: incident reduction 20~30%**
 - **No direct evaluation on traffic improvement such travel time reduction**
 - **Previous work investigated the effect of VLS on FD but the implementation is not valid (Cremer, 1979, 1998);**
 - **To improve left limb of the FD (Hegyi et al, 2003)**





Papamichail et al: Network Traffic

Node: freeway bifurcation and junction



Papamichail et al: 2nd Order Model

$$\rho_i(k+1) = \rho_i(k) + \frac{T}{L\lambda} (q_{i-1}(k) - q_i(k))$$

$$v_i(k+1) = v_i(k) + \frac{T}{\tau} (V(\rho_i(k), b(k)) - v_i(k))$$

$$+ \frac{T}{L} v_i(k) (v_{i-1}(k) - v_i(k)) -$$

$$\frac{1}{\tau} \left(\frac{\nu T}{L} \frac{\rho_{i+1}(k) - \rho_i(k)}{\rho_i(k) + \kappa} \right)$$

- **Density and Speed Model Adopted:**
- where link index is dropped out. i.e. the model is for a fixed link; is section (cell) index;
- Also used in METANET;
- **Problem:** There was no density control variable in the first order model

Papamichail et al: Composite Speed Control Variable

The speed control variable $b(k)$ is imbedded in nonlinear function $V(\rho_i(k), b(k))$ which is the desired speed by average driver.

$$V(\rho_i(k), b(k)) = v_f[b(k)] \cdot \exp \left[-\frac{1}{\alpha[b(k)]} \left(\frac{\rho_i(k)}{\rho_{cr}[b(k)]} \right)^{\alpha[b(k)]} \right]$$

$$v_f[b(k)] = v_f^* \cdot b(k) \Rightarrow b(k) = \frac{v_f[b(k)]}{v_f^*};$$

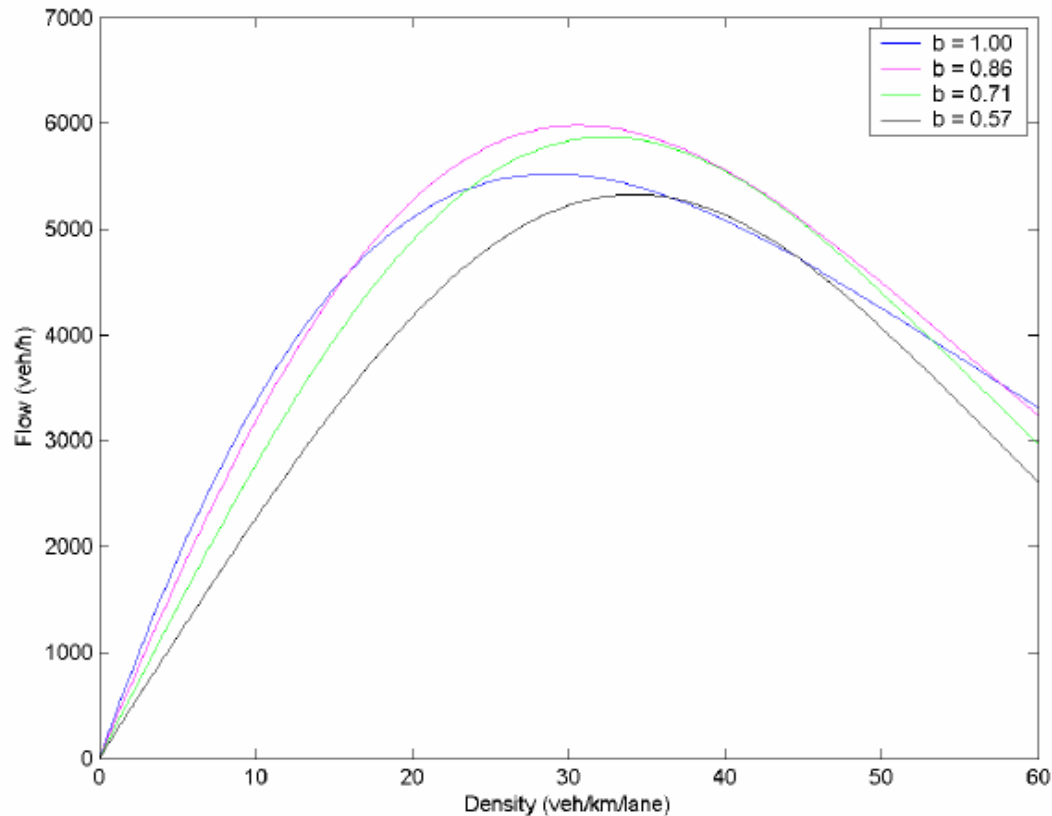
$$b(k) \in [b_{\min}, 1];$$

$$\rho_{cr}[b(k)] = \rho_{cr}^* [1 - 2A(1 - b(k))]$$

$$\alpha[b(k)] = \alpha^* [E - (E - 1)b(k)]$$

Papamichail et al: Expected Control Impact on FD

- No need to assume FD in 2nd order model;
- Impact of VSL control on FD: for different value of control variable $b(k)$ validated with UK M42 data;



Papamichail et al: Onramp Flow and Metering Rate

Onramp (Origin Section of a Link) flow and metering rate:

$$q_r(k) = r(k) \hat{q}_r(k)$$

$$r(k) \in [r_{\min}, 1]: \text{ limit on control}$$

$$\hat{q}_r(k) = \min \{ \hat{q}_1(k), \hat{q}_2(k) \}$$

$$\hat{q}_1(k) = d(k) + w(k) \cdot T: \text{ effected by demand and queue length}$$

$$w(k+1) = w(k) + T \cdot [d(k) - q(k)]: \text{ queue length dynamics}$$

$$\hat{q}_2(k) = Q_o \cdot \min \left\{ 1, \frac{\rho_{\max} - \rho_1(k)}{\rho_{\max} - \rho_{cr}(k)} \right\}; \quad Q_o - \text{ onramp flow capacity}$$



Papamichail et al: Boundary Conditions at a Node of Network:

- Density of last section of a link is determined by the density of the first section of all the leaving links for that node : Spillback effect

$$\rho_{N_m+1}(k) = \frac{\sum_{\mu \in O_n} \rho_{\mu,1}^2(k)}{\sum_{\mu \in O_n} \rho_{\mu,1}(k)}$$

O_n – set of leaving links from node n





Papamichail et al: Boundary Conditions at a Node of Network:

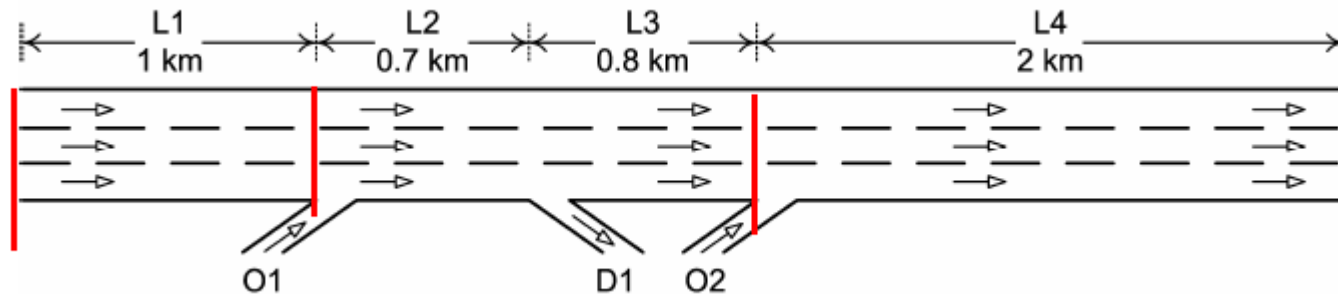
- The first section mean speed is determined by a flow-weighted speed of entering link:

$$v_0(k) = \frac{\sum_{\mu \in I_n} v_{N_\mu}(k) \cdot q_{N_\mu}(k)}{\sum_{\mu \in I_n} q_{N_\mu}}$$

I_n – set of entering links to node n

Papamichail et al: Simulation

- **Freeway configuration**
 - 3 lane freeway;
 - 2 onramp and 1 off-ramp
 - 4 links



Papamichail et al: Objective Function

- **TTS (Total Time Spend with the time horizon)**

$$\begin{aligned}
 J = T \sum_{k=1}^{K_p-1} \sum_m \sum_i \rho_{m,i}(k) L_m \lambda_m + & \quad \text{(TTT)} \\
 T \sum_{k=1}^{K_p-1} \sum_o w_o(k) + & \quad \text{(time due to queue)} \\
 T \sum_{k=1}^{K_p-1} \sum_o \alpha_f [r_o(k) - r_o(k-1)]^2 + & \quad \text{(penalty on RM rate fluctuation)} \\
 T \sum_{k=1}^{K_p-1} \sum_m \alpha_b [b_m(k) - b_m(k-1)]^2 + & \quad \text{(penalty on VSL fluctuation)} \\
 T \sum_{k=1}^{K_p-1} \sum_o \alpha_w [\max\{0, w_o(k) - w_{\max,o}\}]^2 & \quad \text{(penalty on queue limit)}
 \end{aligned}$$

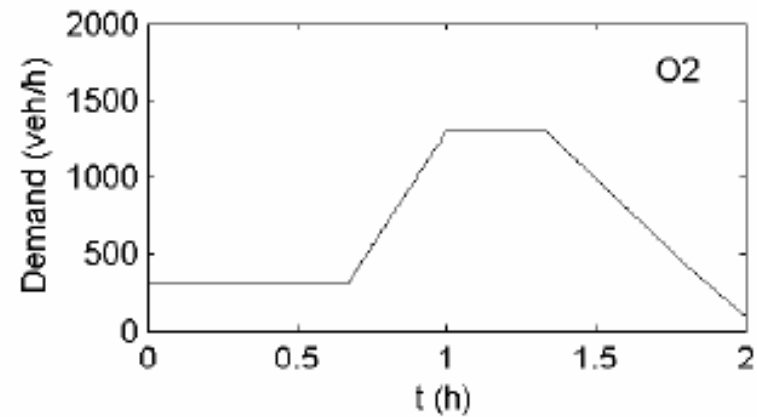
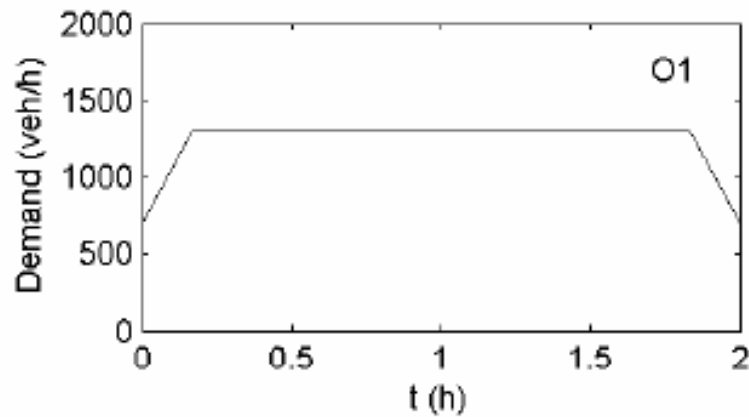


Papamichail et al: Control Strategy

- **Open Loop Optimal Control – Selection the VSL rate and RM rate to minimize the performance index – problem simplified**
- **Uncertainty not directly addressed**
- **Leading to sub-optimal**



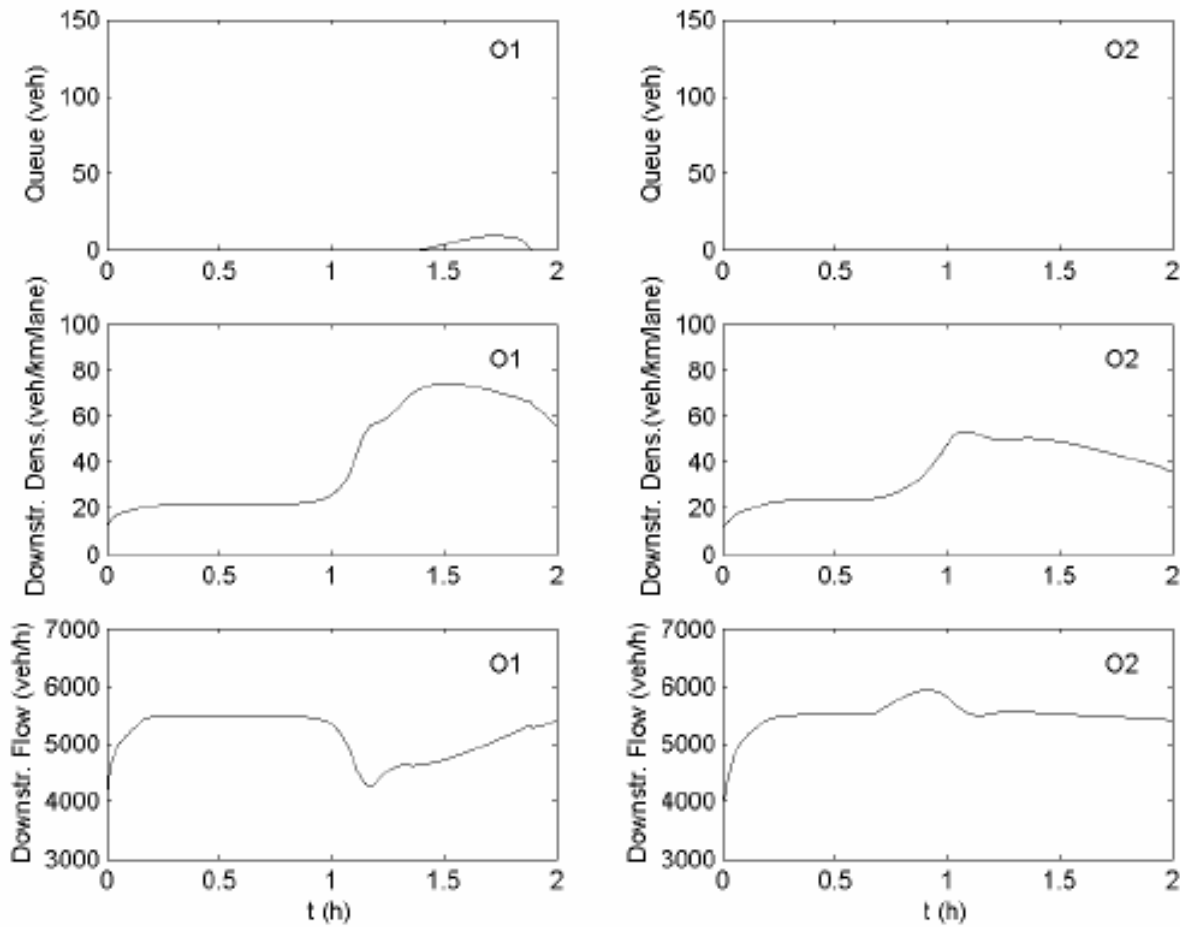
Papamichail et al: Demand on Two Onramps



Trapezoidal demand profiles for the two on-ramps.

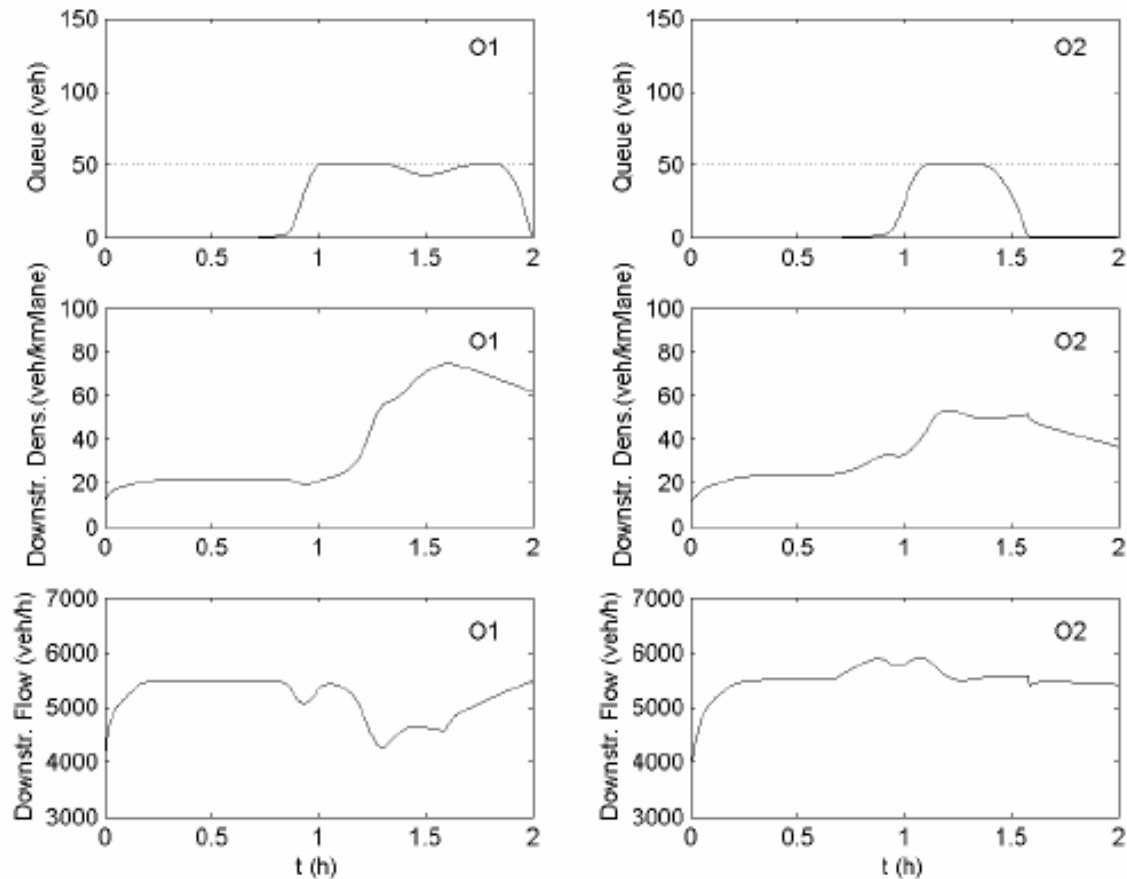
Papamichail et al: Situation without Control

- TTS=1204 veh.h; traffic states in two merge area



Papamichail et al: Ramp Metering Only

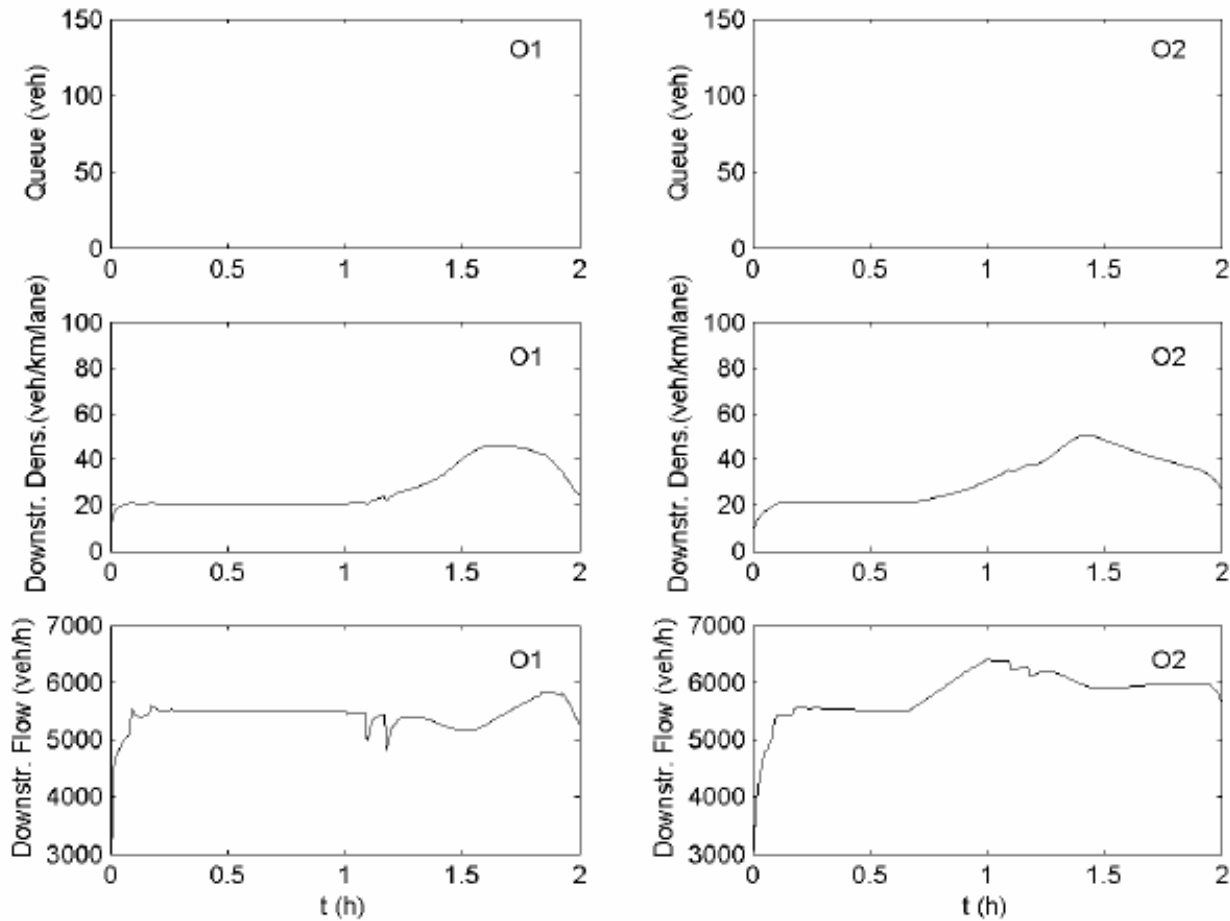
- TTS=1172 veh.h; traffic states in two merge area



Coordinated ramp metering.

Papamichail et al: VSL Only

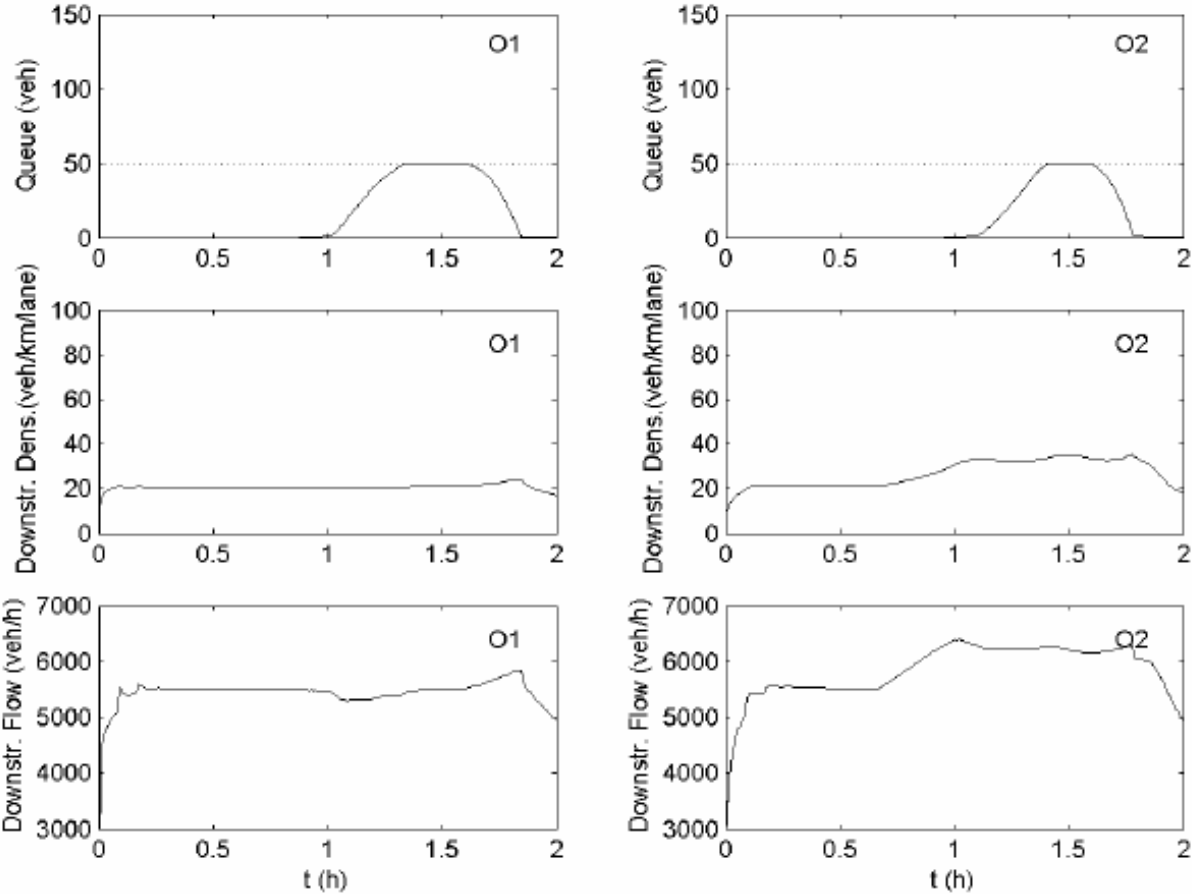
- TTS=741 veh.h; traffic states in two merge area



VSL control.

Papamichail et al: Combined VSL and Ramp Metering

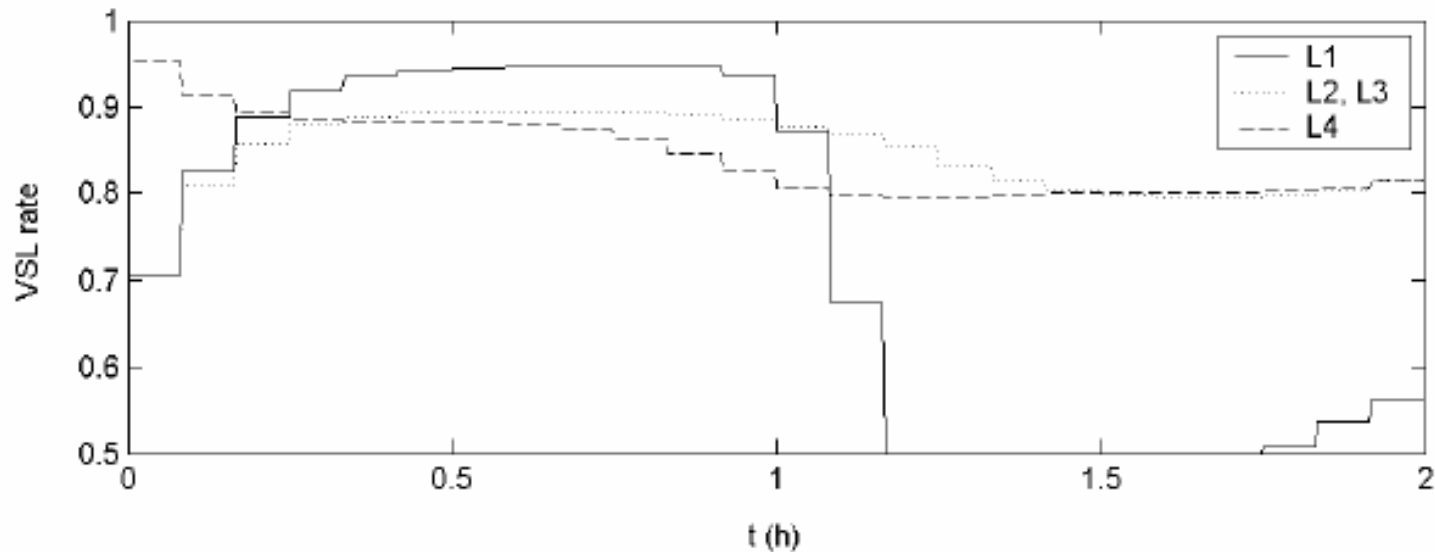
- TTS=673 veh.h; traffic states in two merge area



Integrated control.



Papamichail et al: Optimal VSL Rates for VSL only

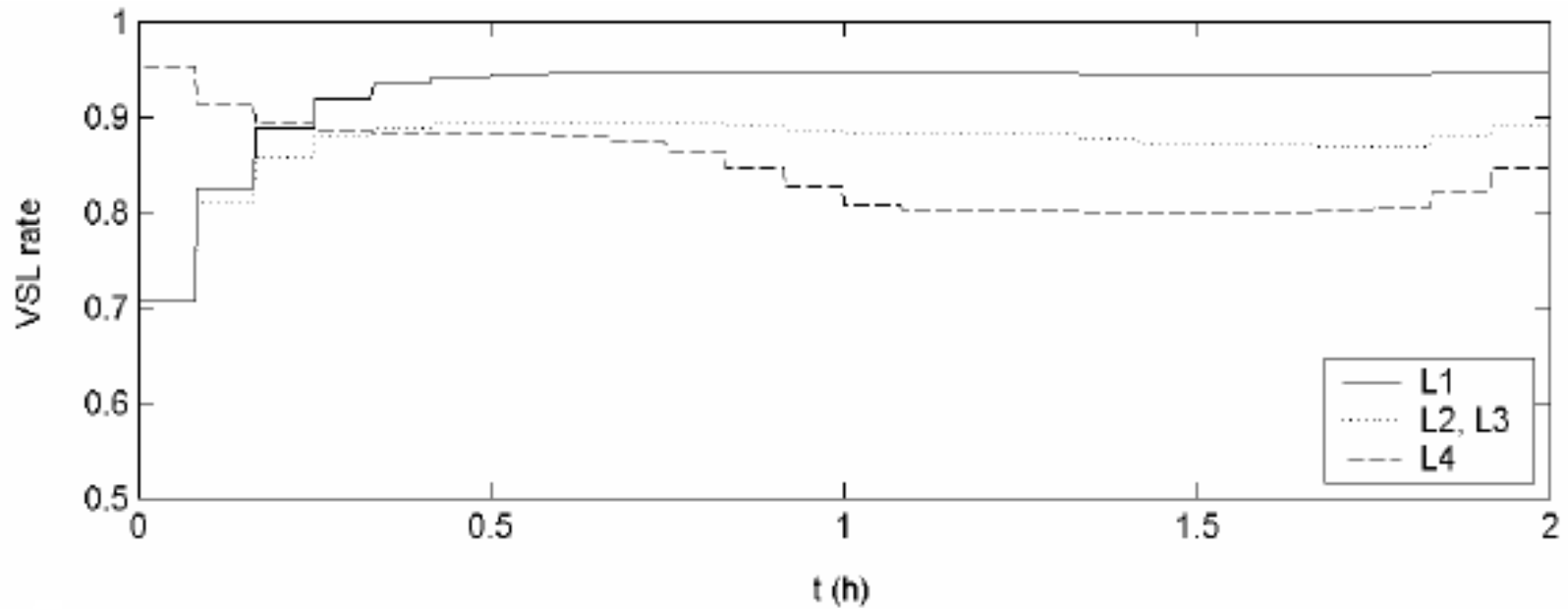


Optimal VSL rates for the VSL control case.





Papamichail et al: Optimal VSL Rates for Combined VSL & RM



Optimal VSL rates for the integrated control case.





Papamichail et al: Summary

- **Simulation claimed to have improved the work in PART I; not implemented yet;**
- **2nd order model validated using real traffic data and remarkably accurate for traffic prediction**
 - **Density and speed dynamics**
 - **Demand model and Queuing model for each onramp**
 - **Mixed Boundary Condition at each node with effect of traffic spill back**
 - **$T=10s$ (model time step)**
 - **Feedback interval: RM – 30s, Ramp Queue length limit: 50veh; VSL – 300s**
- **TTS used as objective function**
- **Finite Time Horizon (2 hrs) Optimal Control – model used for prediction**
- **Efficient numerical algorithm for networks**
- **Performance improvement on TTS compared to no control:**
 - **RM only: 2.7%;**
 - **VSL only: 38.5%**
 - **Combined VSL & RM: 44.1%**

