NC STATE UNIVERSITY

Integrated Corridor Management by Cooperative Traffic Signal and Ramp Metering Control

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STRIDE
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Introduction

- Ramp metering mitigates congestion by directly regulating the entry flow of vehicles into a freeway system
- Ramp Metering affects arterial traffic operation by causing queue spillbacks
- A proper coordination framework for Ramp Metering Controllers and Traffic Signal Controllers can improve traffic operation in a corridor
- Existing literatures lack in providing a demand-responsive real time coordination framework
- An integrated control framework is formulated where all signalized controllers work jointly towards a common goal of improving corridor performance
- Cell Transmission Model (CTM) network loading concept is used to forecast traffic and optimize timings accordingly.

Objectives

Develop a methodology for Integrated Corridor Management that:

- sets demand-responsive timings that maximize network completion of vehicles over time.
- provides a computationally efficient integrated control framework.
- uses Vehicle-to-Infrastructure (V-to-I) connectivity to regulate and coordinate control decisions.

Decision Variables

g_i^t	signal state of intersection cell $i \in C$ at timestep, $t \in T$
g_m^t	metering state of metering cell, $m \in C_M$ at timestep, $t \in T$

State Variables

x_i^t	number of vehicles in cell $i \in C$ at time step $t \in T$
y_{ij}^t	number of vehicles advancing from cell $i \in C$ to cell j at time step $t \in T$

Problem Formulation

- Objective function:

$$\max\ Z = \sum_{\forall i \in C_s} \sum_{\forall t \in T} x_i^t$$

- Flow conservation constraints

$$x_i^{t+1} = x_i^t + (\delta_{io} + \delta_{is}) \sum_{k \in P(i)} y_{ki}^t - (\delta_{ir} + \delta_{io}) \sum_{j \in S(i)} y_{ij}^t + \delta_{ir} D_i^t \quad \forall t \in T, \forall i \in C, \forall o \in C\backslash\{C_s, C_r\}, \forall r \in C_r, \forall s \in C_s$$

- Flow feasibility constraints

$$\textstyle\sum_{j \in S(i)} y_{ij}^t \le x_i^t \qquad \forall i \in C\backslash C_s, t \in T$$

$$\textstyle\sum_{j \in S(i)} y_{ij}^t \le Q_i^t \qquad \forall i \in C\backslash C_s, t \in T$$

$$\textstyle\sum_{i \in P(j)} y_{ij}^t \le Q_j^t \qquad \forall j \in C\backslash C_r, t \in T$$

$$\textstyle\sum_{i \in P(j)} y_{ij}^t \le \rho(N_j - x_j^t) \qquad \forall j \in C\backslash C_r, t \in T$$

$$y_{ij}^t = \beta_j^t \textstyle\sum_{k \in S(i)} y_{ik}^t \qquad \forall j \in C_i, i \in P(j), t \in T$$

- Signal timing constraints

$$g_i^t = g_j^t \qquad \forall (i,j) \in R, t \in T$$

$$g_i^t + g_j^t \le 1 \qquad \forall k \in I, i \in E(k), j \in O(i), t \in T$$

$$\textstyle\sum_{\tau=t+1}^{t+G_{min}} g_i^\tau \ge (g_i^{t+1} - g_i^t) G_{min} \qquad \forall k \in I, i \in E(k), t \in T, t \le |T| - G_{min}$$

$$\textstyle\sum_{\tau=t}^{t+G_{max}+1} g_i^\tau \le G_{max} \qquad \forall k \in I, i \in E(k), t \in T, t \le |T| - G_{max}$$

$$q_i^t = g_i^t Q_i^t \qquad \forall i \in C_i, t \in T$$

- Ramp metering rate constraints

$$\textstyle\sum_{m \in F(k)} g_m^t \le L(\mathrm{k}) \qquad \forall k \in M, t \in T$$

$$\textstyle\sum_{\tau=t+1}^{t+G_{min}^{ramp}} g_m^\tau \ge (g_m^{t+1} - g_m^t)\, G_{min}^{ramp} \qquad \forall k \in M, m \in F(k), t \in T, t \le |T| - G_{min}^{ramp}$$

$$\textstyle\sum_{\tau=t}^{t+G_{max}^{ramp}+1} g_m^\tau \le G_{max}^{ramp} \qquad \forall k \in M, m \in F(k), t \in T, t \le |T| - G_{max}^{ramp}$$

$$q_m^t = g_m^t Q_m^t \qquad \forall m \in C_M, t \in T$$

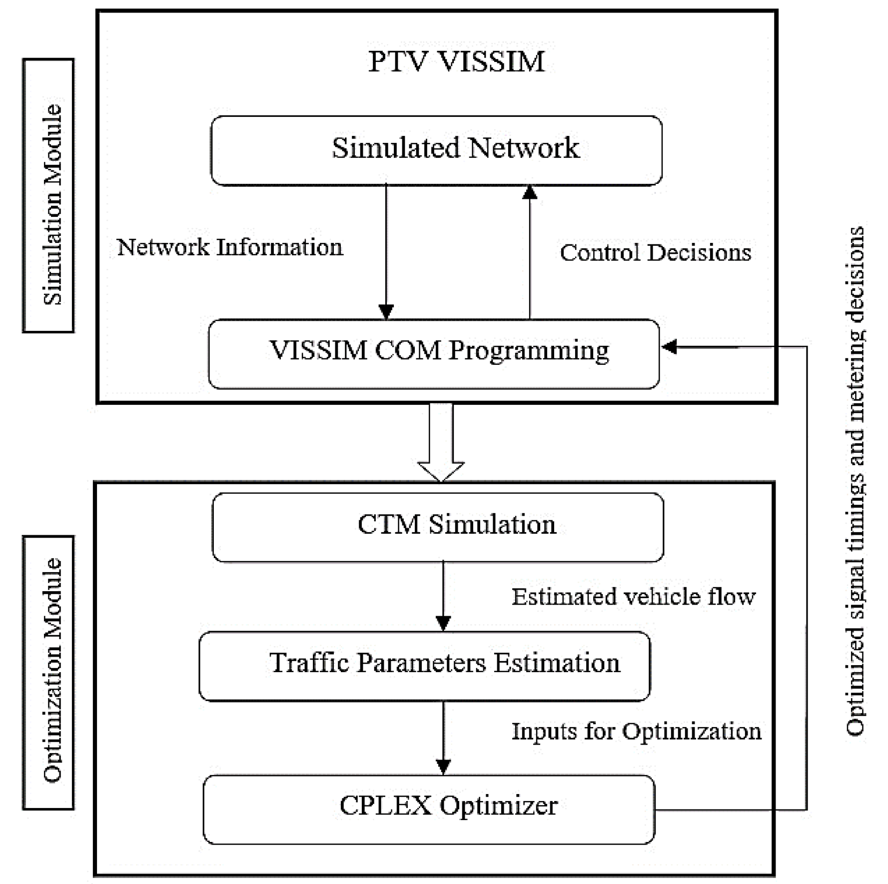
- Non-negativity & Integrality constraints

$$x_i^t \ge 0, y_{ij}^t \ge 0 \qquad \forall i \in C, j \in S(i), t \in T$$

$$g_m^t \in \{0,1\}, g_i^t \in \{0,1\} \qquad \forall m \in C_m, t \in T, \forall i \in C_i, t \in T$$

Solution Technique

- Receding horizon framework



Case Study

- San Mateo, CA testbed
- Benchmarking scenarios:

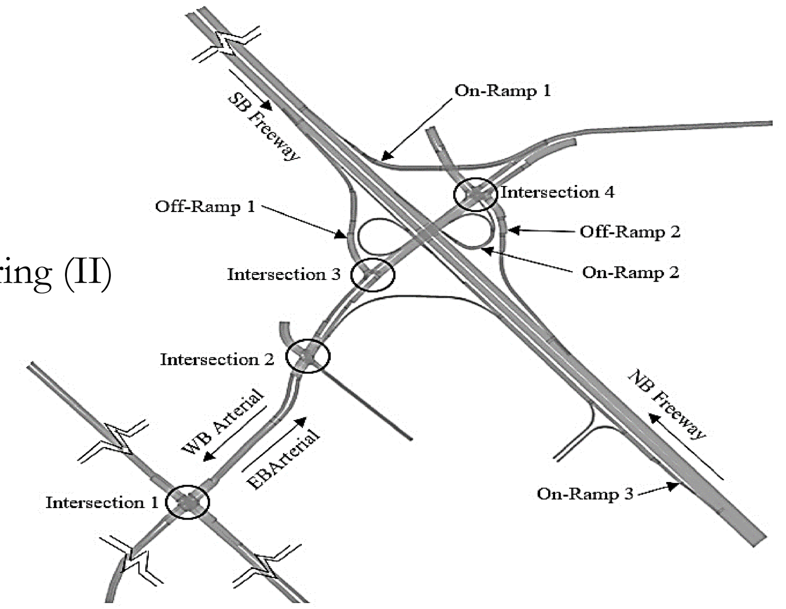
— Existing control (I)

— Existing control with no metering (II)

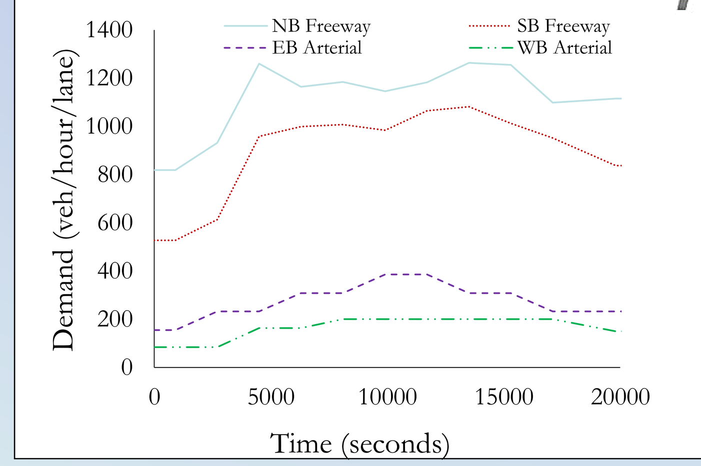
— Optimal Metering control (III)

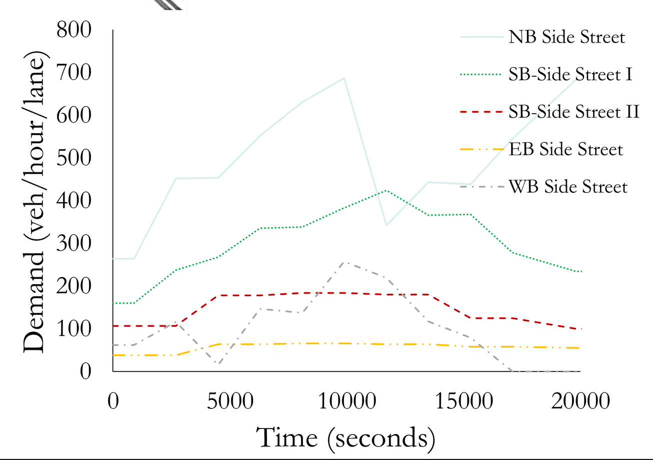
— Optimal Signal control (IV)

— Integrated control (V)



- Demand Plan:



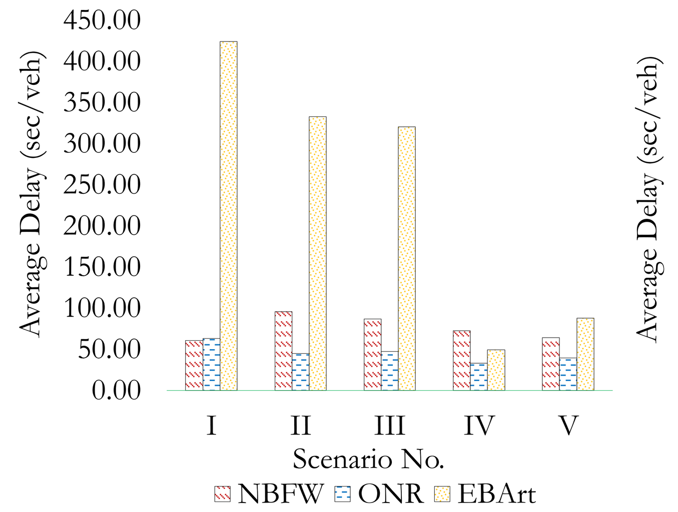


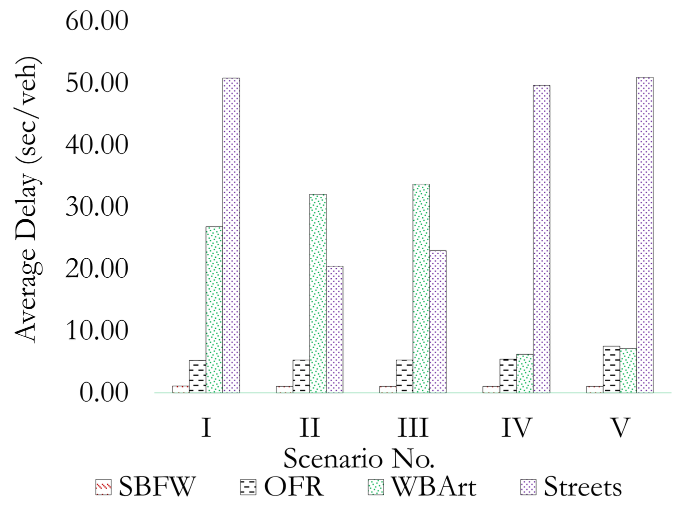
Results

- Corridor-wide performances

Performance Measures	Existing Control	Existing Signal control with No metering	Optimal Metering	Optimal Signal Control	Integrated
	I	II	III	IV	V
Average Delay (sec)	78.3	78.9	75.1	52.2	52.3
Average Stops	4.3	4.3	4.0	2.6	2.7
Average Speed (mph)	28.2	27.9	28.6	33.2	33.3
Throughput (vehicles)	79406	79374	79490	79612	79618
Total Delay (hours)	2121.65	2139.43	2029.64	1369.3	1374.14
Total Travel Time (hours)	4559.65	4583.6	4476.4	3806.7	3813.12
Total Stops (stops)	414957	415355	389762	240788	257511

- Direction-wise performances





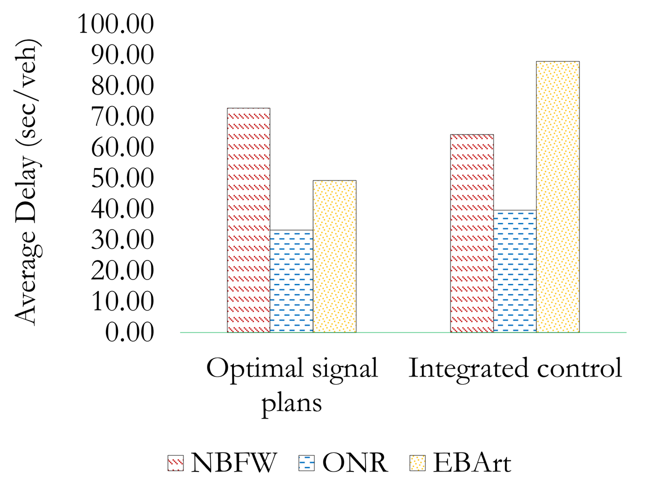
- Integrated Control vs Optimal Signal Control

— Integrated Control

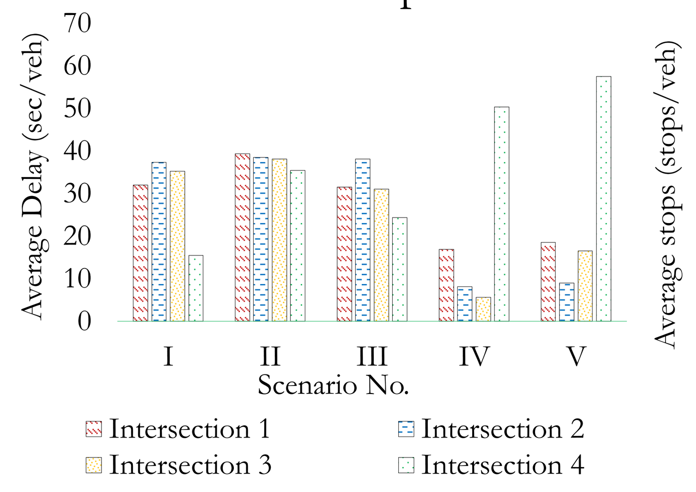
- Arterial delay reduction: 79%
- Freeway delay increase: 5%

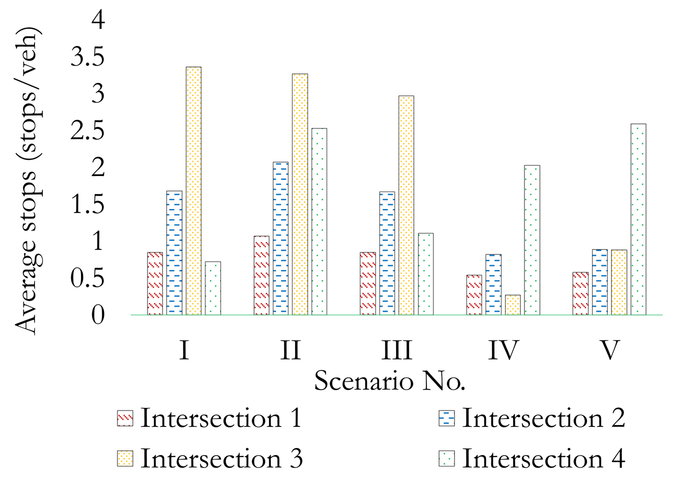
— Optimal Signal control

- Arterial delay reduction: 88%
- Freeway delay increase: 19%

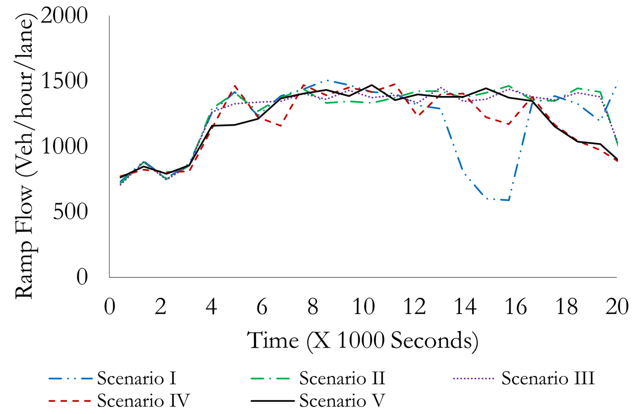


- Intersection-level performance

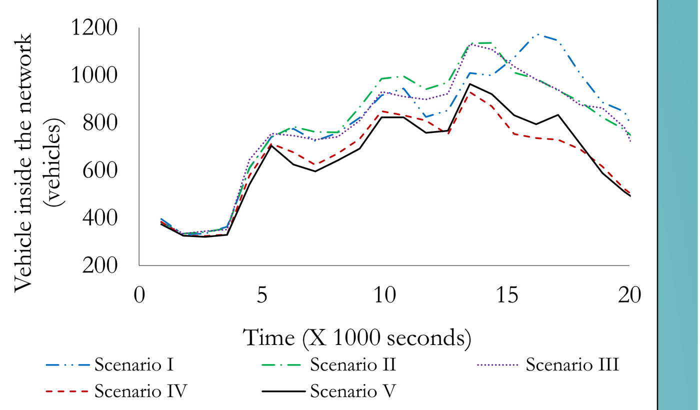




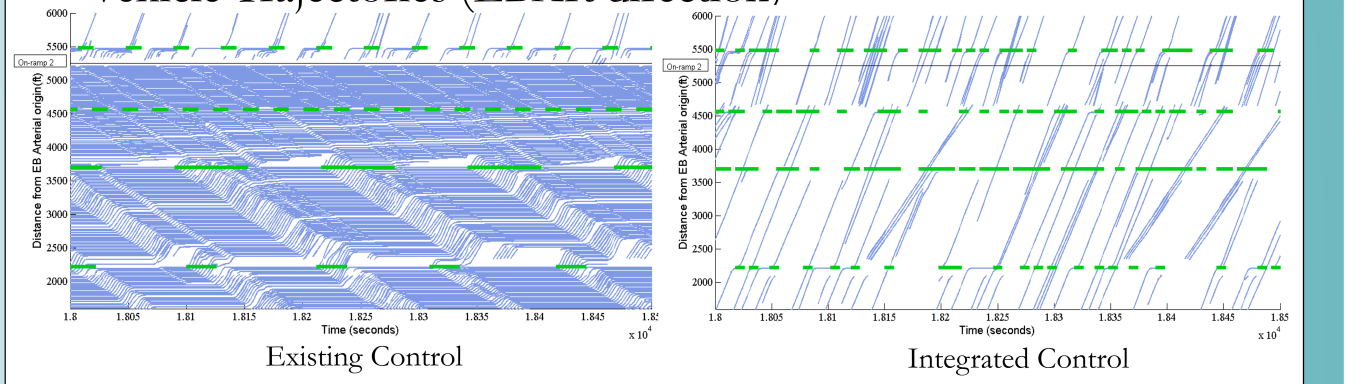
- Ramp flows



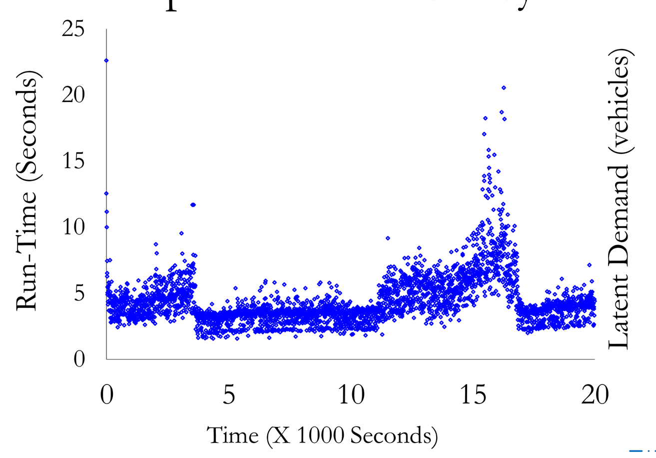
- Vehicle accumulation



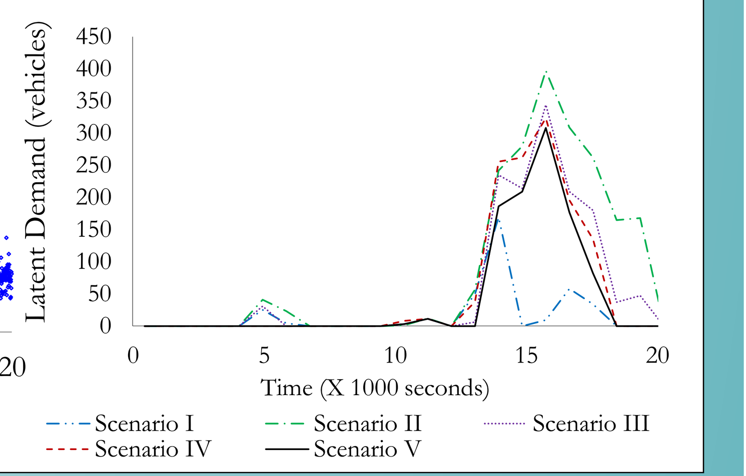
- Vehicle Trajectories (EBArt direction)



- Computational efficiency



- Latent Demand



Conclusion

- The integrated control reduces average delay, average stops, travel times by 33%, 36%, and 16%, respectively when compared to existing control condition
- It reduces highly congested arterial delay by 79% with an increase of the freeway delay of 5%
- The methodology can be applied in real-time as the average run time is 4.4 seconds with CTM resolution of 6 seconds

Advanced Transportation Lab for Automated Systems (ATLAS)