Minimizing Freeway Corridor Delays While Balancing Mainline and On-Ramp Flows

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- Implementing Regulator Approaches
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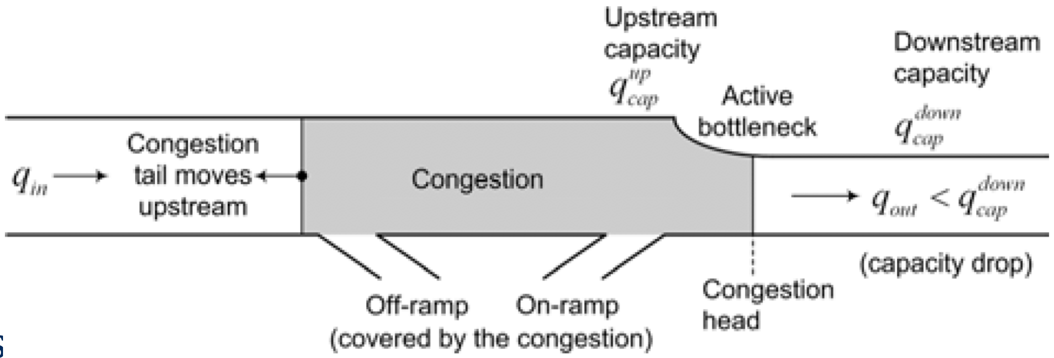
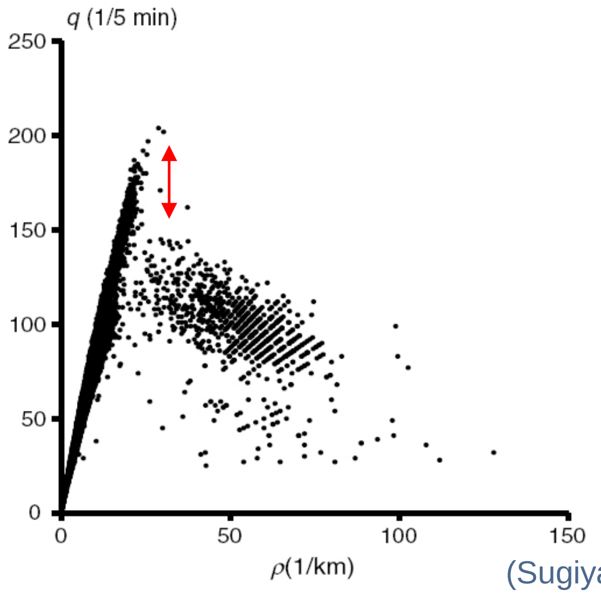
Source of Freeway Congestion & Solution

- **Issue:**
  - **Bottleneck**: a location where flow capacity upstream *is greater than* flow capacity downstream of the bottleneck location $(q_{cap}^{up}) > (q_{cap}^{down})$
  - If $q_{in} > q_{cap}^{down}$ → bottleneck is activated → congestion is formed → $q_{out} < q_{cap}^{down}$.
  - Effects on Freeway:
    - Capacity drop (CD) at the congestion head
    - Blocking of off-ramps
- **Solution:**
  - Cut total demand ($q_{ramp} + q_{mainstream}$) to q_{cap}
    - Via Ramp Metering (RM) → Control on-ramp flow
      - Issue: Ramp queues → Congestion spilling back
    - Via Variable Speed Limit (VSL) → Control mainstream flow
      - Issue: Cannot handle higher demand scenarios



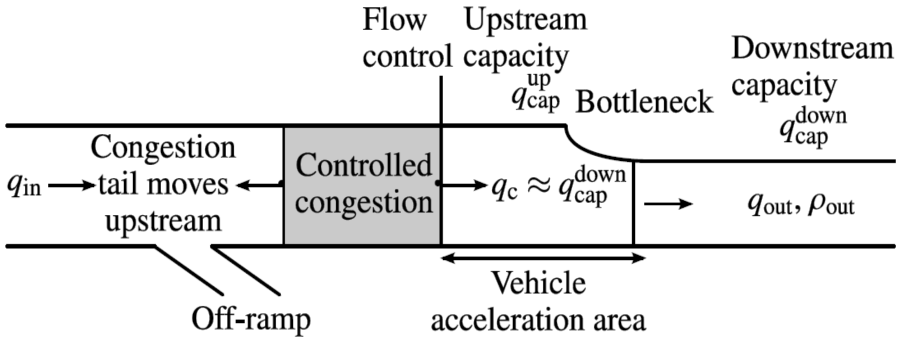
(R C Carlson et al., 2009)



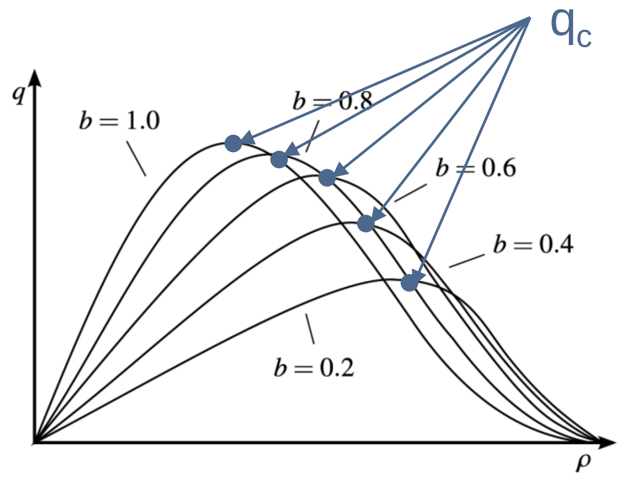
(Sugiyamal et al., 2008)

How VSL Works

- Basic idea:
  - To pace upstream traffic into downstream bottlenecks without triggering congestion by setting $q_c \cong q_{cap}$ to avoid the CD and establish maximum bottleneck throughput.



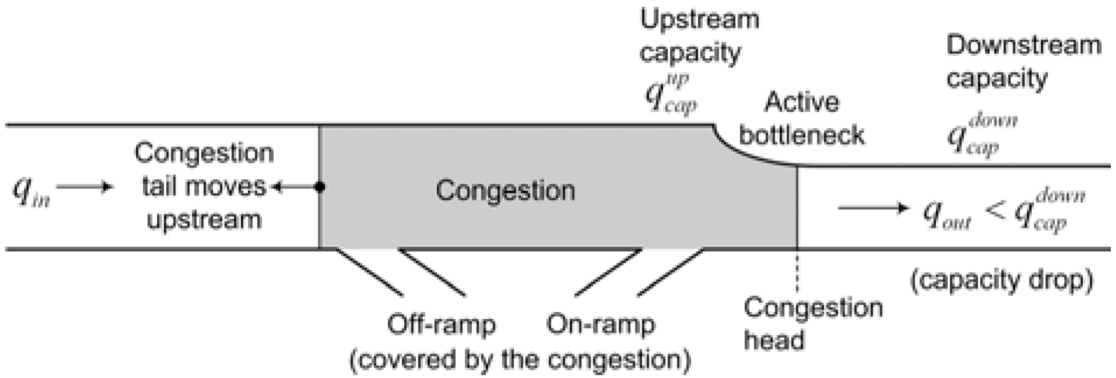
- Effects of VSL on traffic flow:
  - Decreasing the slope of flow density curve
  - Critical density is shifted to higher values
  - Lower flow capacity in fundamental diagram



(Rodrigo C. Carlson et al., 2013)

Numerical Example

- Given a 3-lane freeway:
  - Total capacity = 6000 $\frac{veh}{hr}$ (2000 $\frac{veh}{hr}$ /lane)
  - Mainstream demand ($q_{in\ (main)}$) = 5500 $\frac{veh}{hr}$
  - On-ramp demand ($q_{in\ (ramp)}$) = 1500 $\frac{veh}{hr}$

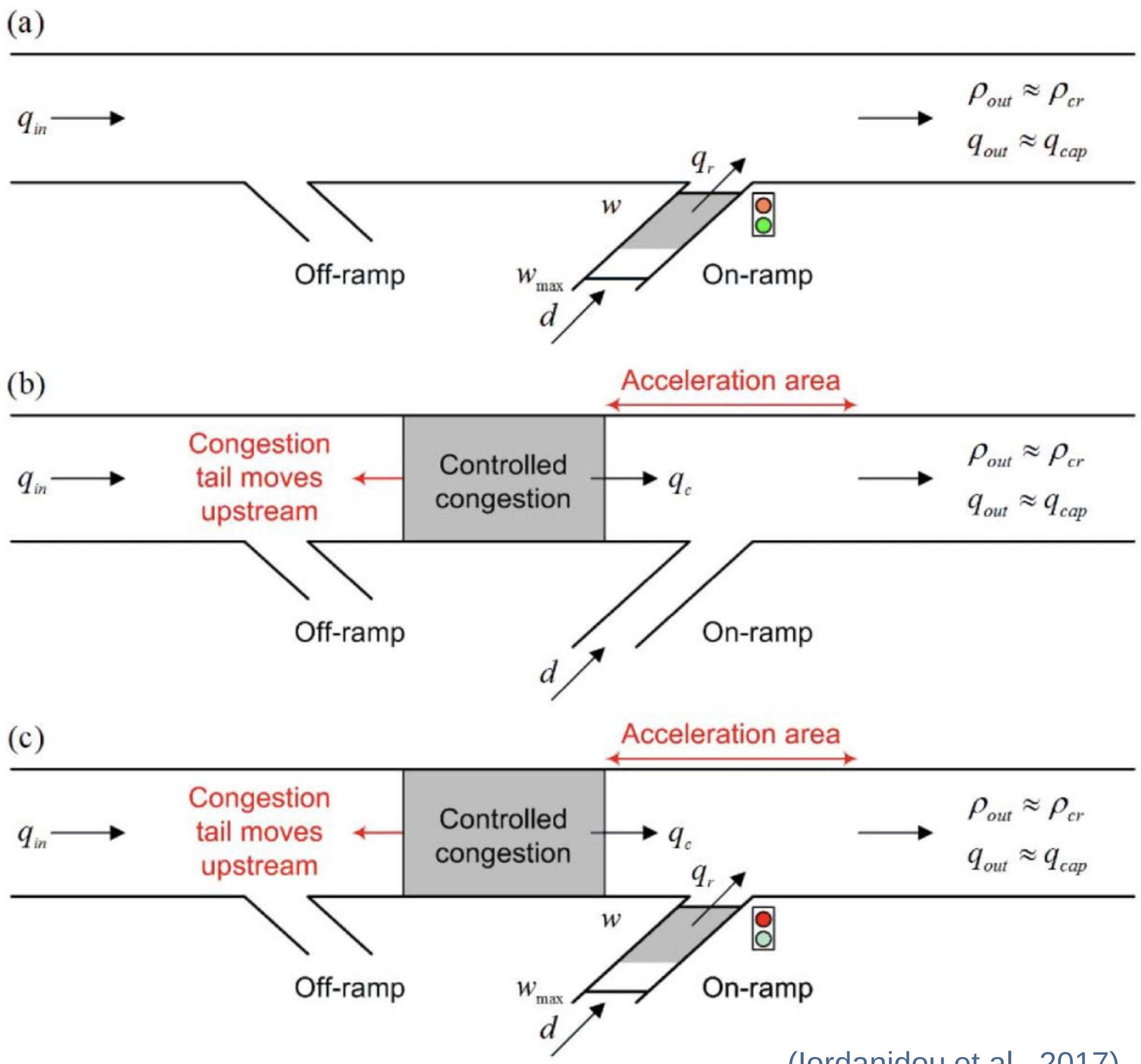


- Without Control:
  - Bottleneck is activated
  - Output flow (q_{out}) << Capacity (6000 $\frac{veh}{hr}$) due to capacity drop
  - Congestion is formed and its tail moves upstream blocking off-ramps

(R C Carlson et al., 2009)

Numerical Example

- A. RM:
  - Avoid CD by cutting q_r to 500 $\frac{veh}{hr}$
  - $q_{out} \cong$ Capacity $\cong 6000 \frac{veh}{hr}$
- B. MTFC by VSL
  - Avoid CD by cutting q_c to 4500 $\frac{veh}{hr}$
  - $q_{out} \cong$ Capacity $\cong 6000 \frac{veh}{hr}$
- C. Cooperation of RM and VSL
  - Designed so that $q_r + q_c \cong 6000 \frac{veh}{hr}$



(Iordanidou et al., 2017)

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Implementing Regulator Approach

- RM:
  - Simple regulator controller Alinea is implemented
    - I-type structure to calculate ramp flow r at instant k

$$r(k) = r(k-1) + K_I e_o(k)$$

- VSL
  - Simple regulator I-type structure to calculate VSL rate b at instant k

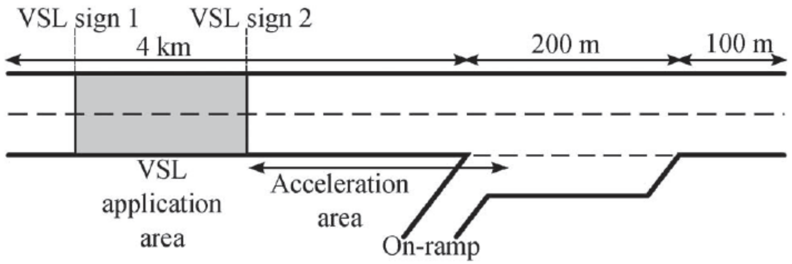
$$b(k) = b(k-1) + K_I e_o(k)$$

- Cooperation of RM and VSL
  - Alinea RM is applied first till failing to achieve its target then VSL kicks in
- Both controllers (RM and VSL) are implemented using Aimsun Application Programming Interface (API)

(Eduardo R. Müller et al., 2016; Eduardo Rauh Müller et al., 2015)

Our Implementation

- Simple hypothetical network from literature:
  - The implemented controller is tested on the same network to replicate literature outcomes
    - 4.3 km long
    - 300 m application's area length
    - 200 m acceleration's area length
- Network with real geometry
  - The controller is then tested on a selected onramp from QEW
    - Winston Churchill onramp



(Eduardo R. Müller et al., 2016)

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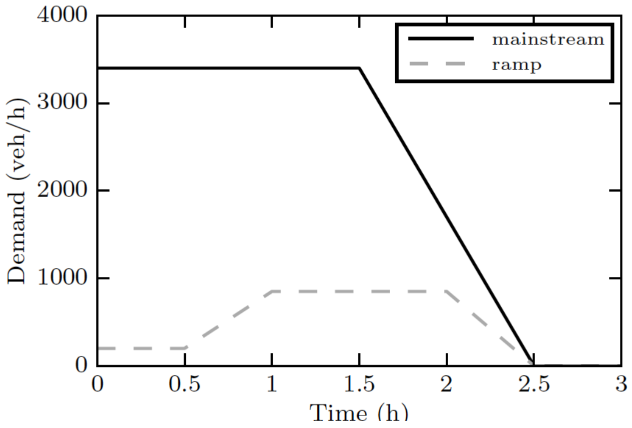
Applying VSL Only (Lit. Results)

Network Demand



3500 peak mainstream demand
1000 peak on ramp demand

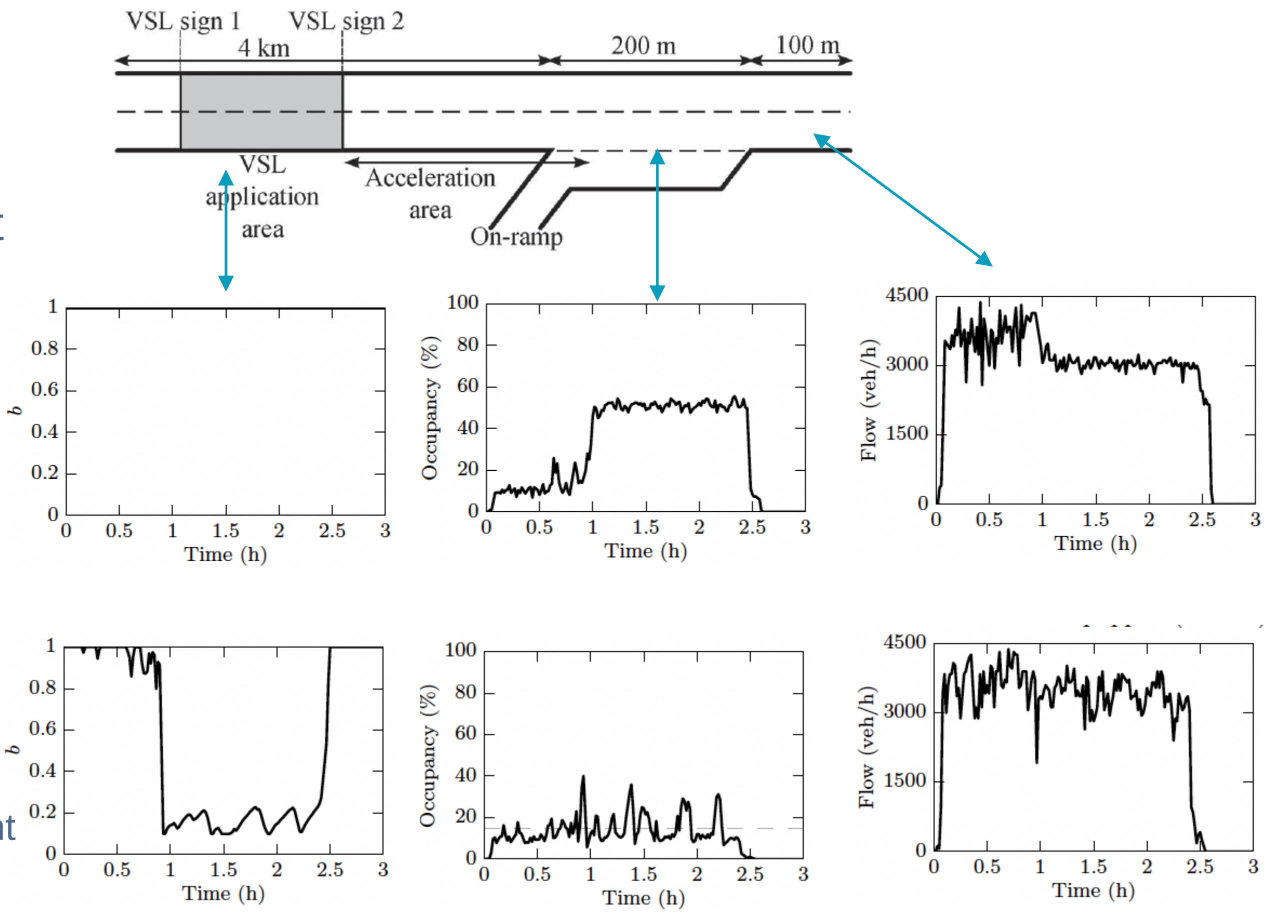
Literature Output

Base case

Average delay
143.7 sec/km

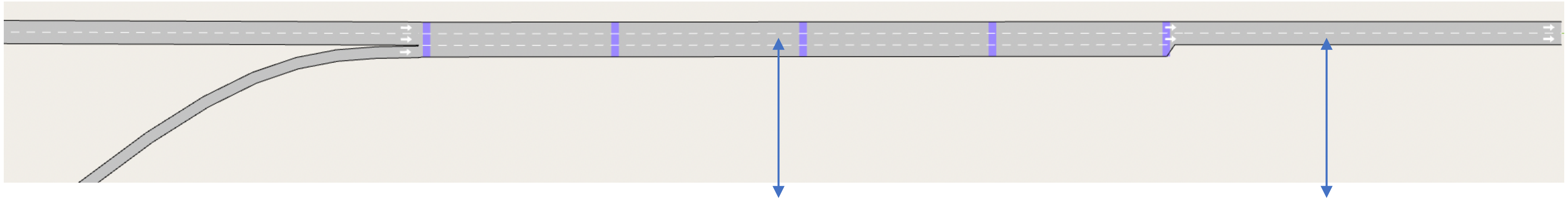
Controlled

Average delay
72.9 sec/km
49% improvement



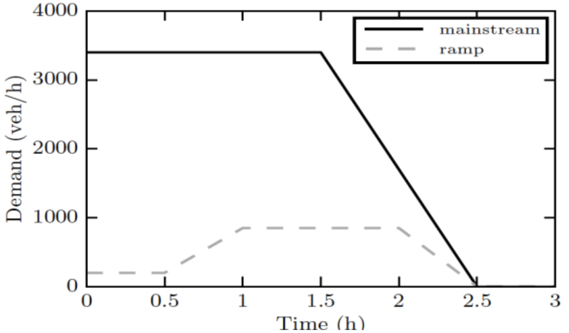
(Eduardo R. Müller et al., 2016)

Base Case No-Control (Lit. Network)



- **Average delay = 129 sec/km**

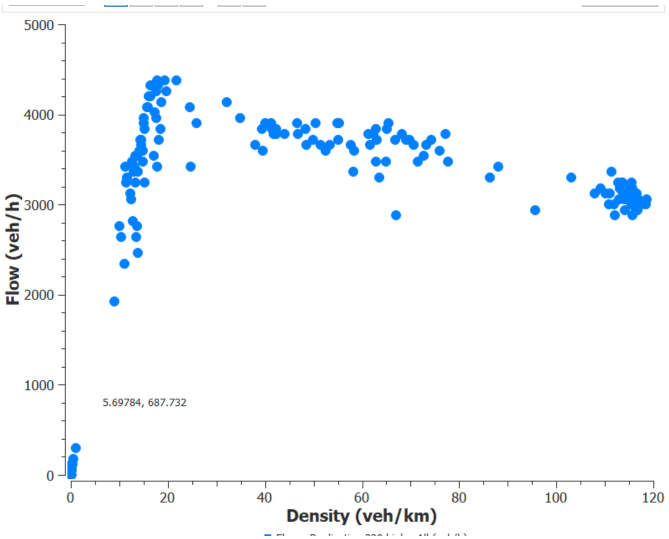
Network Demand



3500 peak mainstream demand
1000 peak on ramp demand

(Eduardo R. Müller et al., 2016)

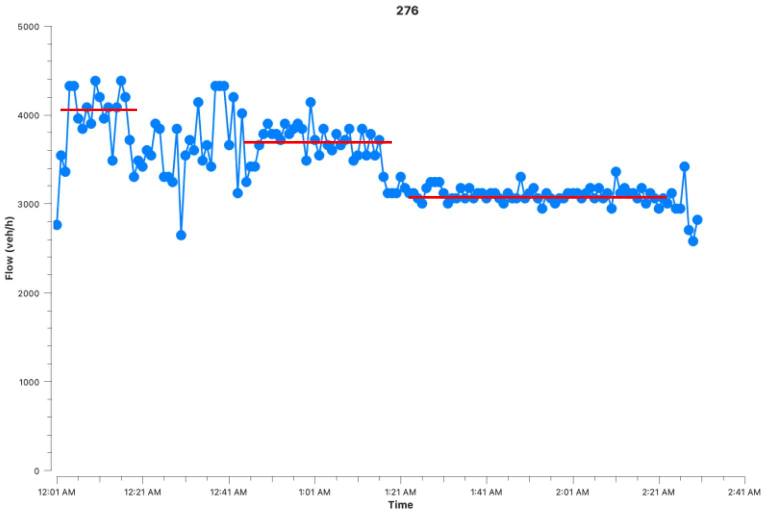
FD for merging section



Capacity $\approx 4000 \frac{veh}{hr}$

Critical density $\approx 22 \frac{veh}{km}$

Outflow from bottleneck



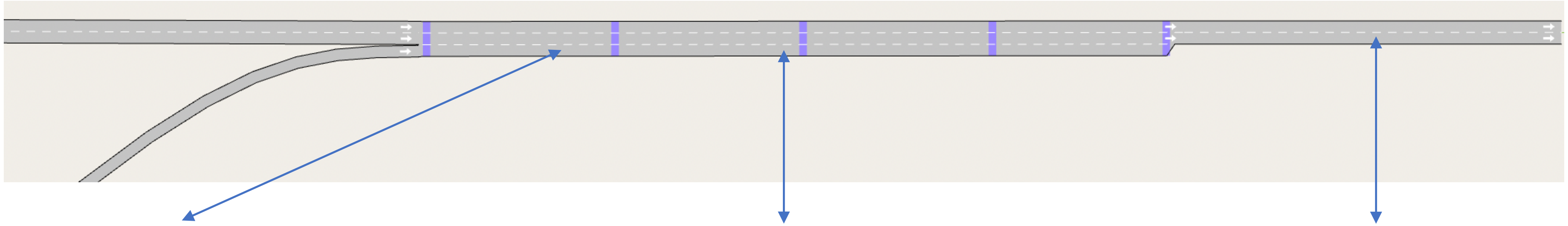
Max. outflow $\approx 4000 \frac{veh}{hr}$

Fell to $\approx 3700 \frac{veh}{hr}$

Then fell further to $\approx 3000 \frac{veh}{hr}$

Applying VSL Only (Lit. Network)

- Average delay is 68 sec/km (47.3% improvement)



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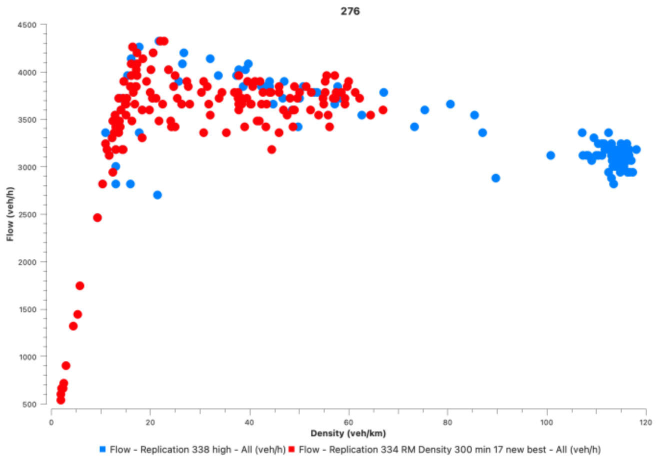
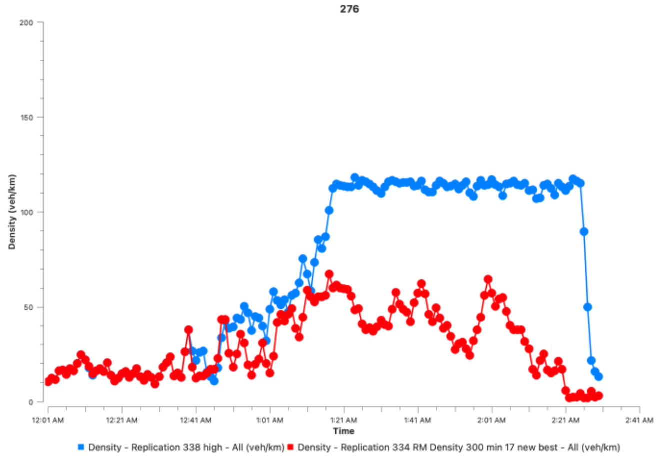
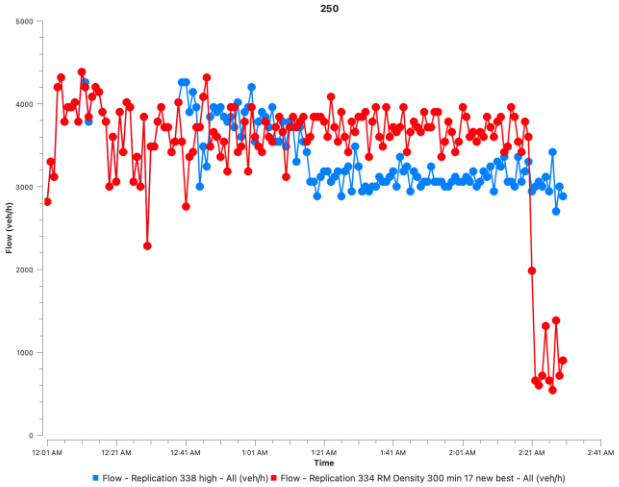


Density at merging section



Outflow from bottleneck

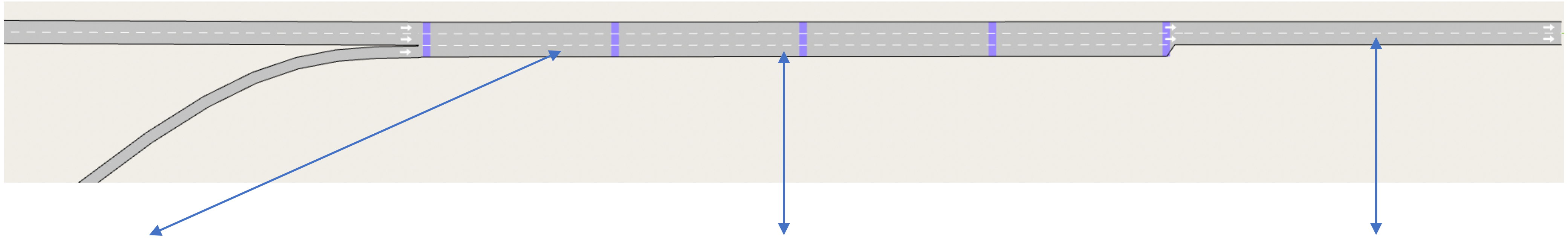


Higher demand scenario **(Lit. Network)**

- Increasing mainstream peak demand from 3500 $\frac{veh}{hr}$ to 4000 $\frac{veh}{hr}$ and on ramp peak demand from 1000 $\frac{veh}{hr}$ to 1400 $\frac{veh}{hr}$ leads to:
  - Decrease in the performance of VSL from 47.3% improvements in delays to 3.53% improvements in delays
    - New base case scenario average delay: 163.15 sec/km
    - New controlled scenario average delay: 157.39 sec/km
- The higher the demand, the harder it is for VSL to function

Applying RM only **(Lit. Network)**

- Average delay is 71 sec/km (45% improvement)



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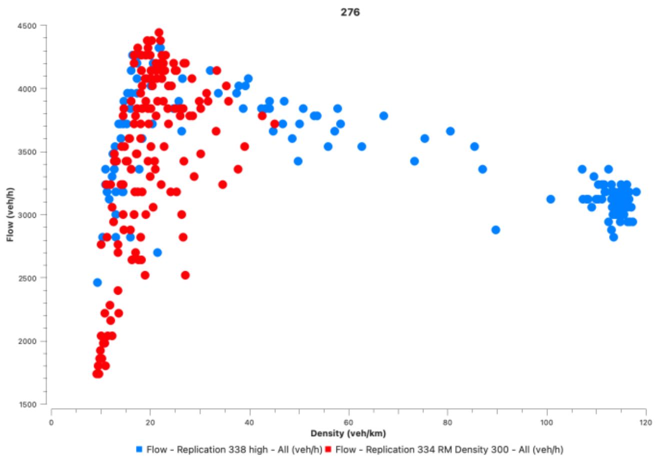
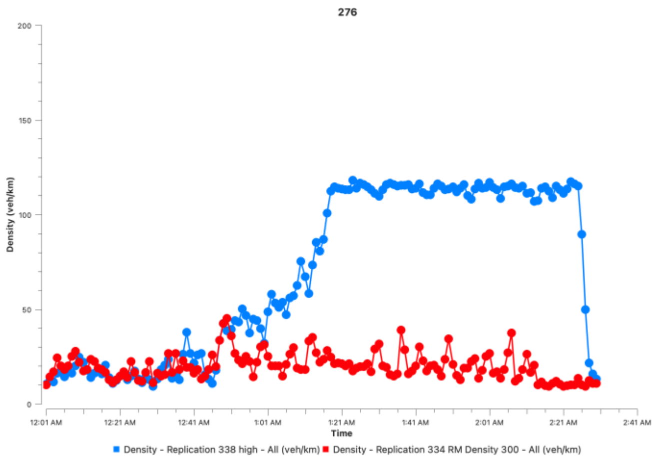
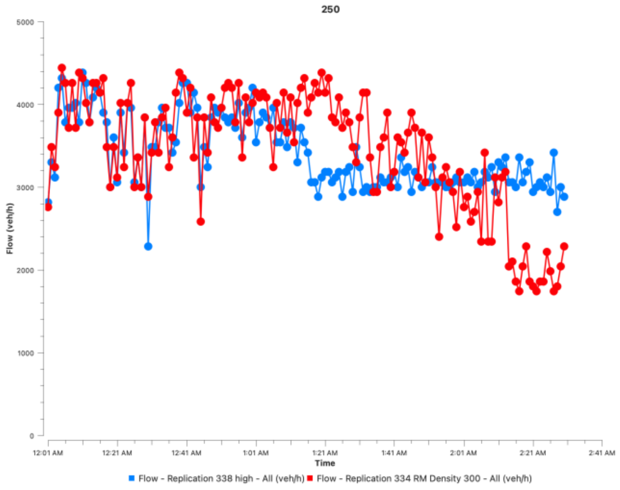


Density at merging section

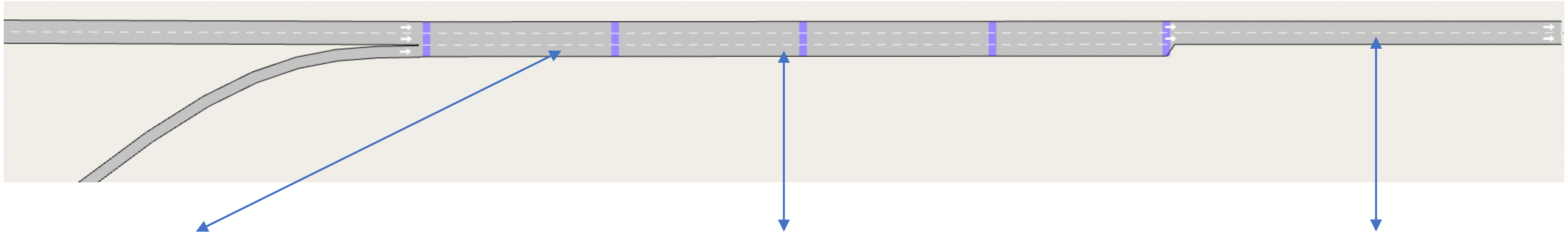


Outflow from bottleneck



Applying RM with queue management **(Lit. Network)**

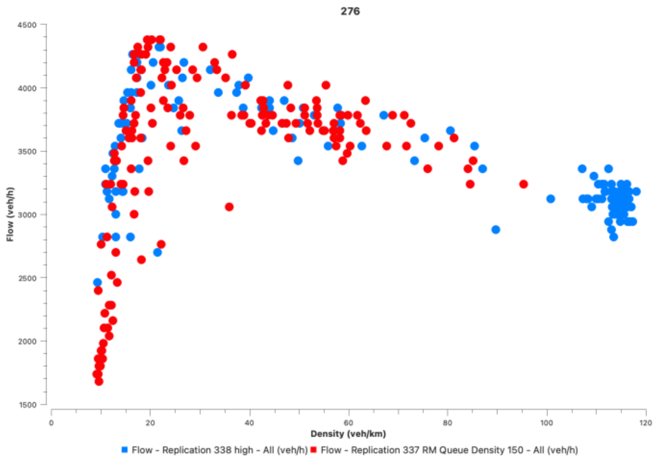
- Average delay is 86 sec/km (33% improvement)

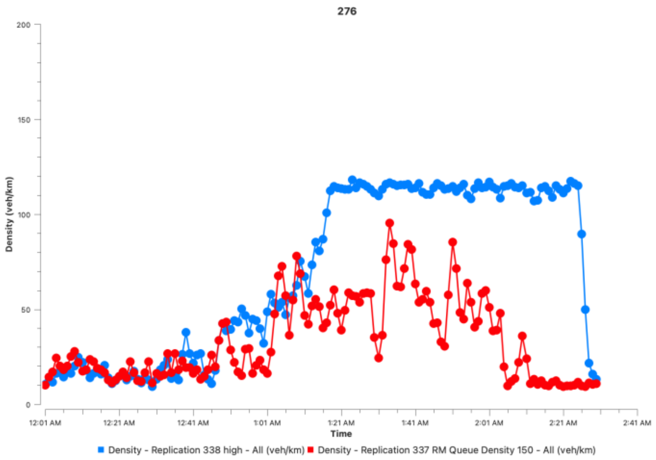


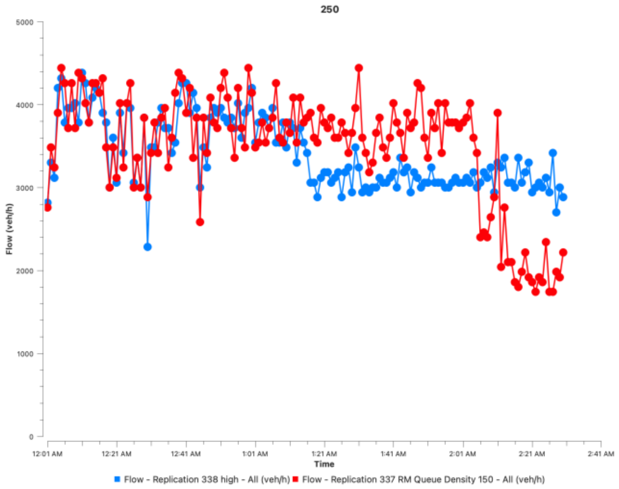
FD for merging section

Density at merging section

Outflow from bottleneck

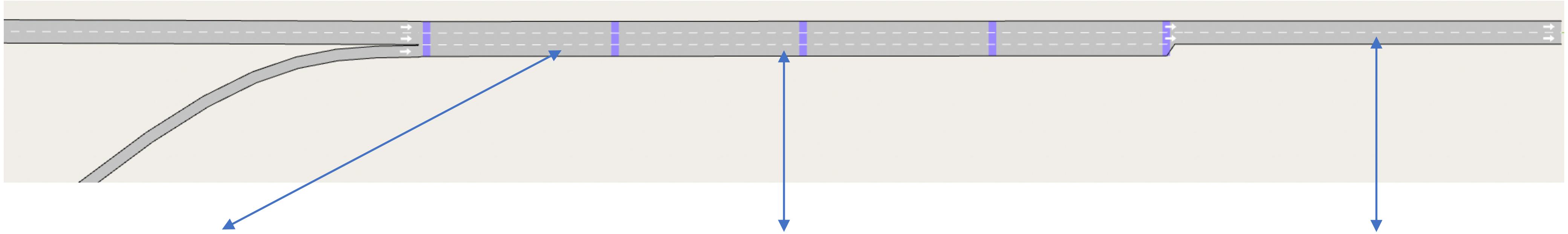






Applying RM and VSL **(Lit. Network)**

- Average delay is 79 sec/km (39% improvement)



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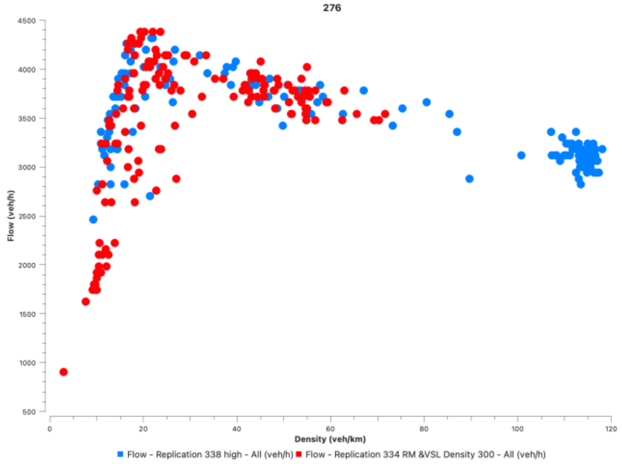
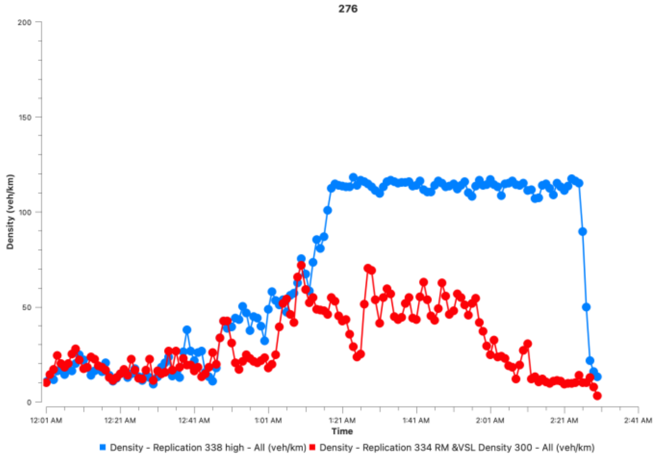
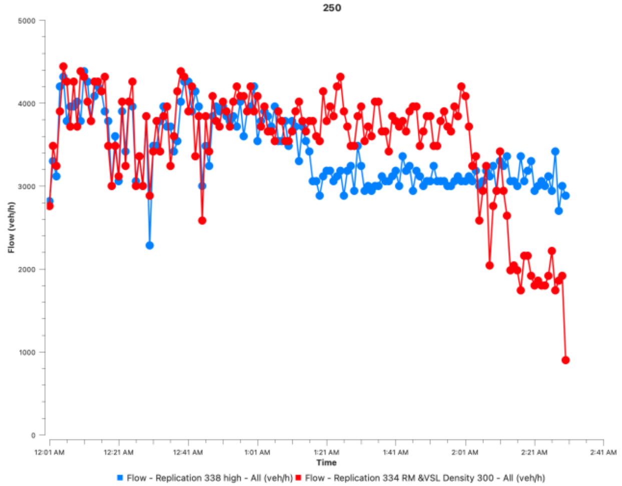


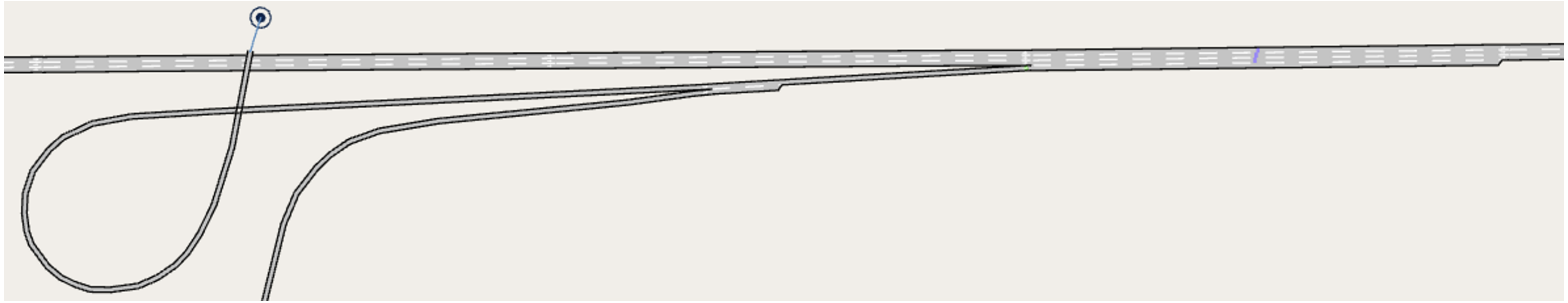
Density at merging section



Outflow from bottleneck

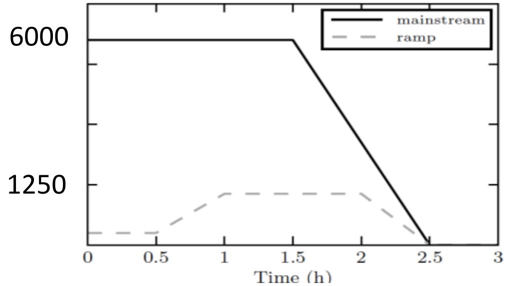


Base Case No-Control (Churchill Network)

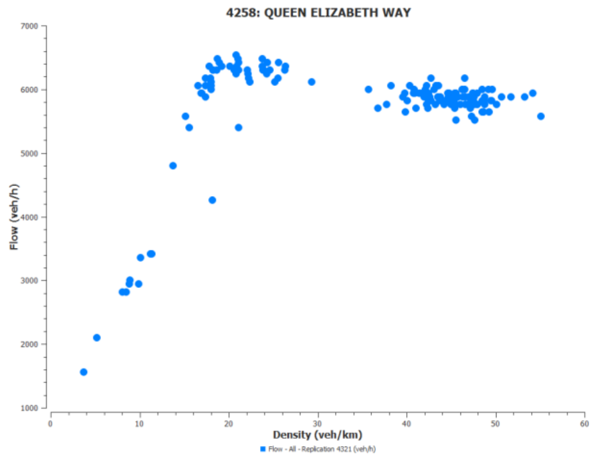


- **Average delay = 67 sec/km**

Network Demand

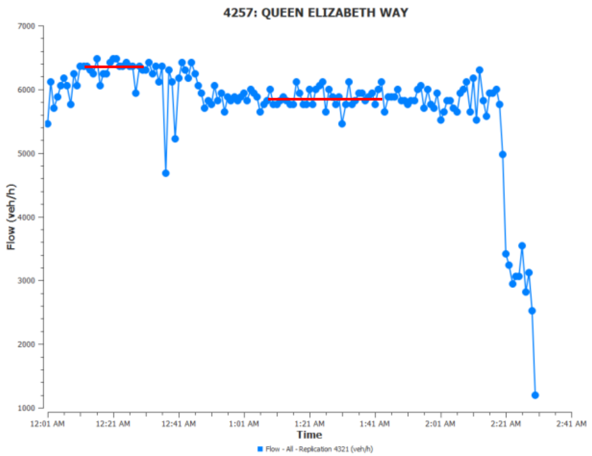


6000 peak mainstream demand
1250 peak on ramp demand



Capacity $\approx 6200 \frac{veh}{hr}$

Critical density $\approx 21 \frac{veh}{km}$

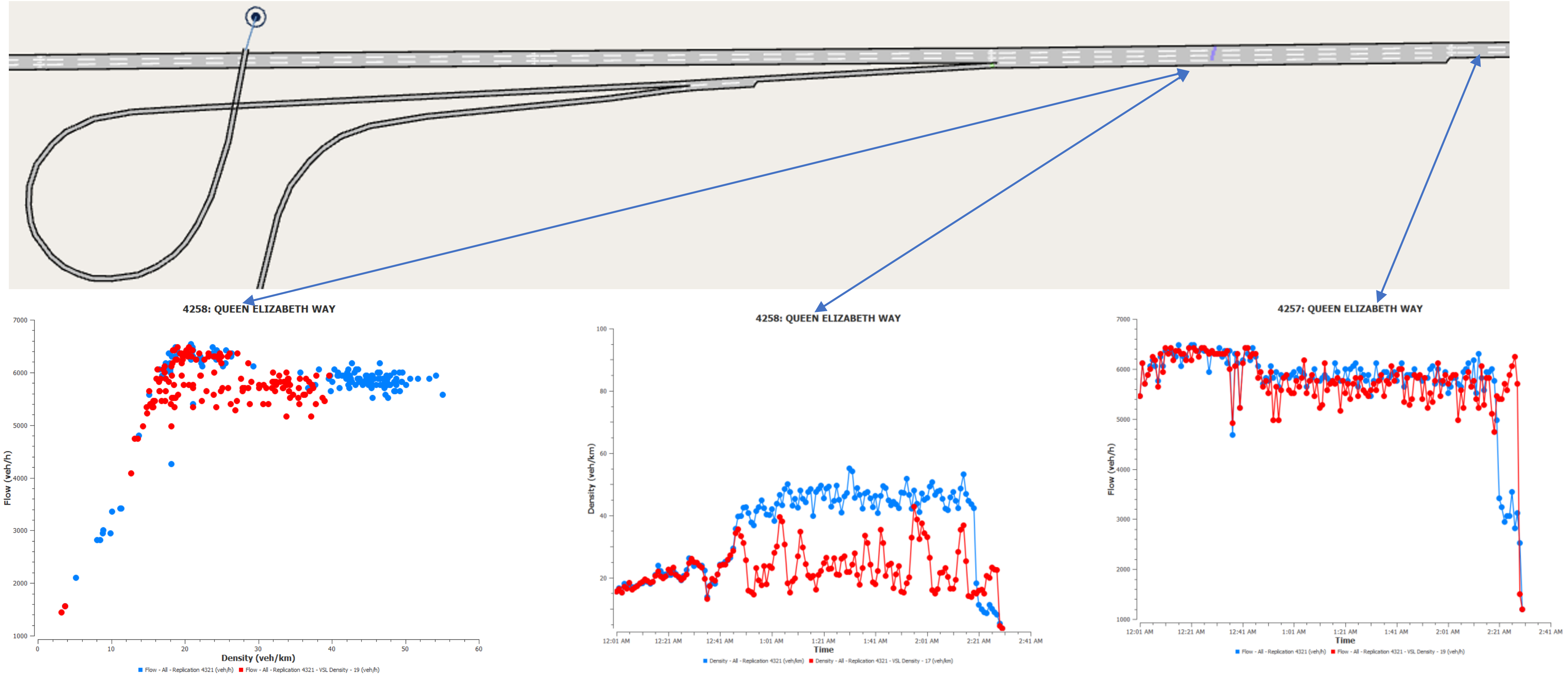


Max. outflow $\approx 6200 \frac{veh}{hr}$

Fell to $\approx 7700 \frac{veh}{hr}$

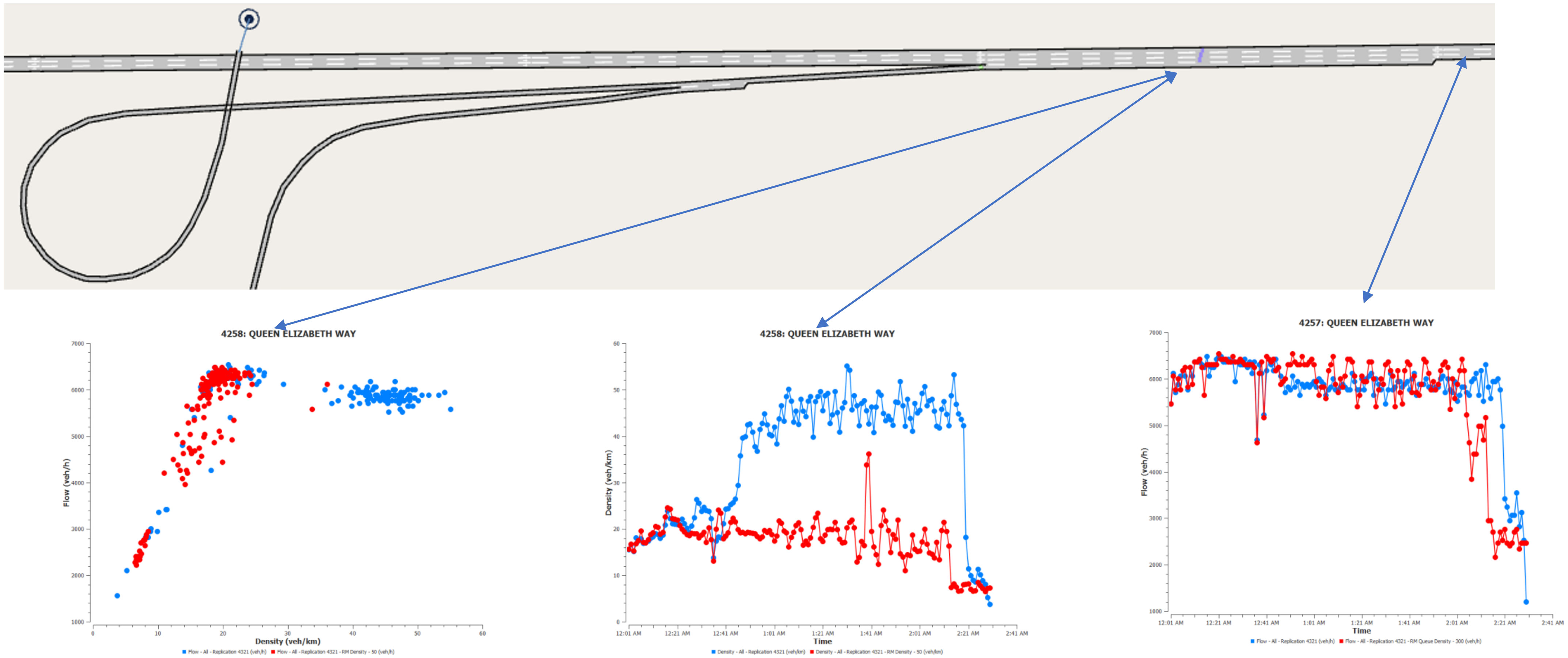
Applying VSL Only (Churchill Network)

- Average delay is 56 sec/km (16.4% improvement)



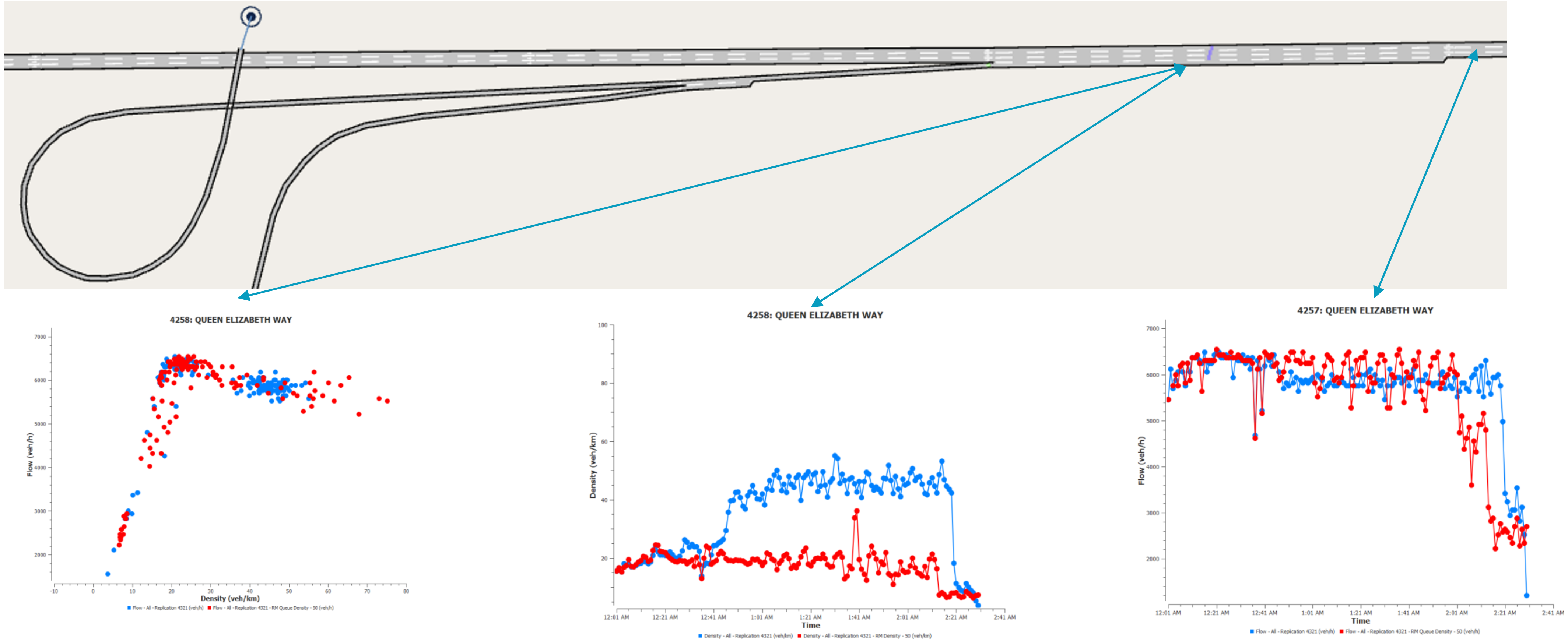
Applying RM only (Churchill Network)

- Average delay is 38 sec/km (43.2% improvement)



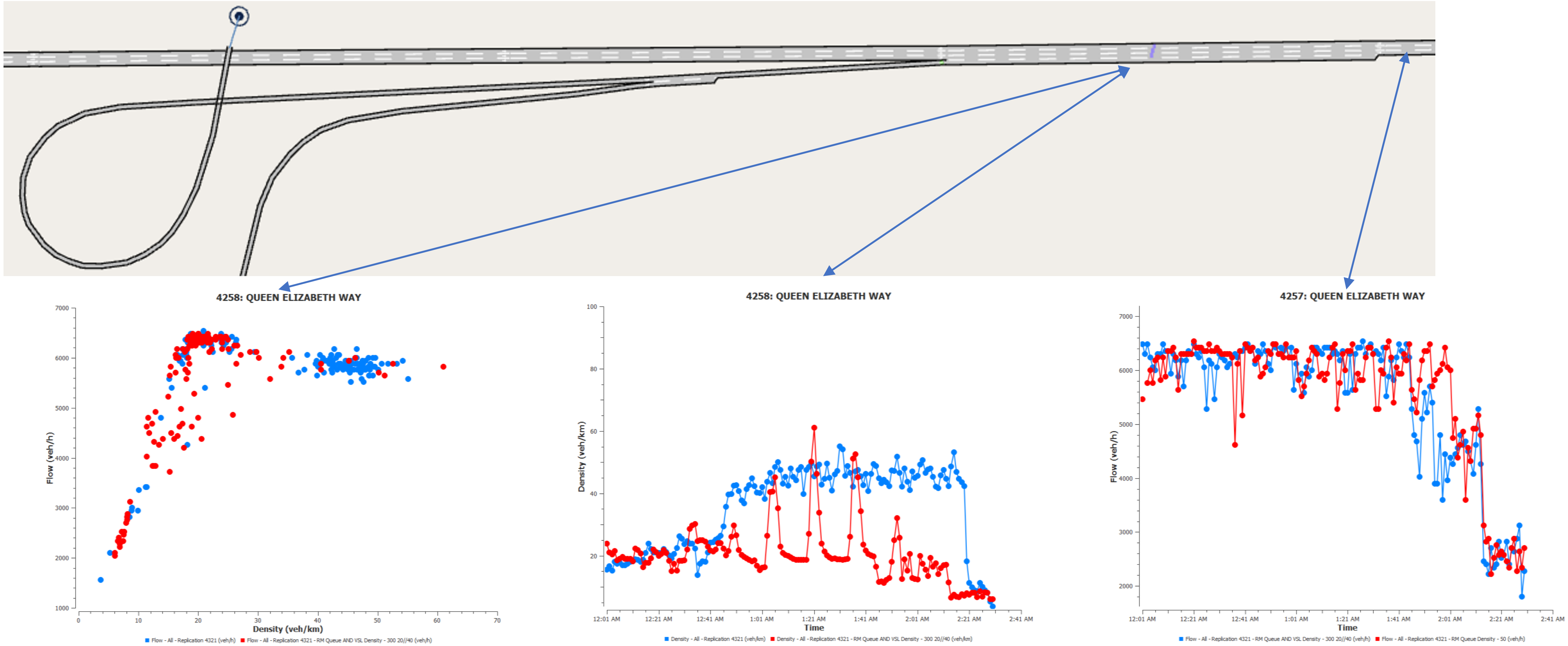
Applying RM with queue management (Churchill Network)

- Average delay is 54 sec/km (19.4% improvement)



Applying RM and VSL (Churchill Network)

- Average delay is 47 sec/km (30% improvement)

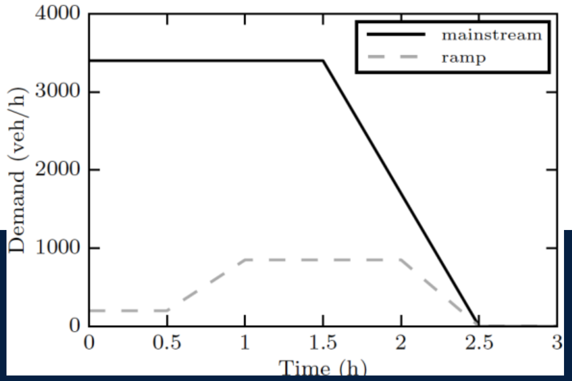


Summary of results

Control	Lit. Network Average Delays		Churchill Network Average Delays	
Base case	129	77	67	51
		398		151
VSL	68 (47.3%)	80	56 (16.4%)	66
		22		13
RM	71 (45%)	5	38 (43.2%)	8
		404		280
RM + Queue	86 (33.3%)	28	54 (19.4%)	27
		351		240
RM + Queue + VSL	79 (38.8%)	25	47 (30%)	22
		326		233

3500 mainstream demand
1000 on ramp demand

6000 mainstream demand
1250 on ramp demand



Summary of results

Any control is better than none

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VSL gives priority to ramp demand

3500 mainstream demand
1000 on ramp demand

6000 mainstream demand
1250 on ramp demand

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The more the number of lanes the less effective is VSL

3500 mainstream demand
1000 on ramp demand

6000 mainstream demand
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Summary of results

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		326		233

RM gives priority to mainline demand

3500 mainstream demand
1000 on ramp demand

6000 mainstream demand
1250 on ramp demand

Summary of results

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Queue management deteriorated RM

3500 mainstream demand
1000 on ramp demand

6000 mainstream demand
1250 on ramp demand

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3500 mainstream demand
1000 on ramp demand

6000 mainstream demand
1250 on ramp demand

Cooperation can balance benefits

Conclusions

- Either RM or VSL will reduce corridor delays
  - In higher demand scenarios VSL alone may not be enough
- Choosing the best approach (ie RM, VSL or both) depends on:
  - Agency priority (ex. Downtown Toronto at pm peak ramp flow can be more important than mainstream flow)
  - Freeway Vs Ramp flow proportional (ex. 401 delaying 4 lanes can increase total average delays)

Next Steps

- Implementing other VSL controllers that can suppress oscillations
- Solving some Aimsun API bugs
- Apply previously discussed controllers on full freeway
- Develop more advanced AI/RL controller for RM, VSL and cooperation between both

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Thank you for listening!

Questions