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Integrating Vehicle Control with Traffic Management

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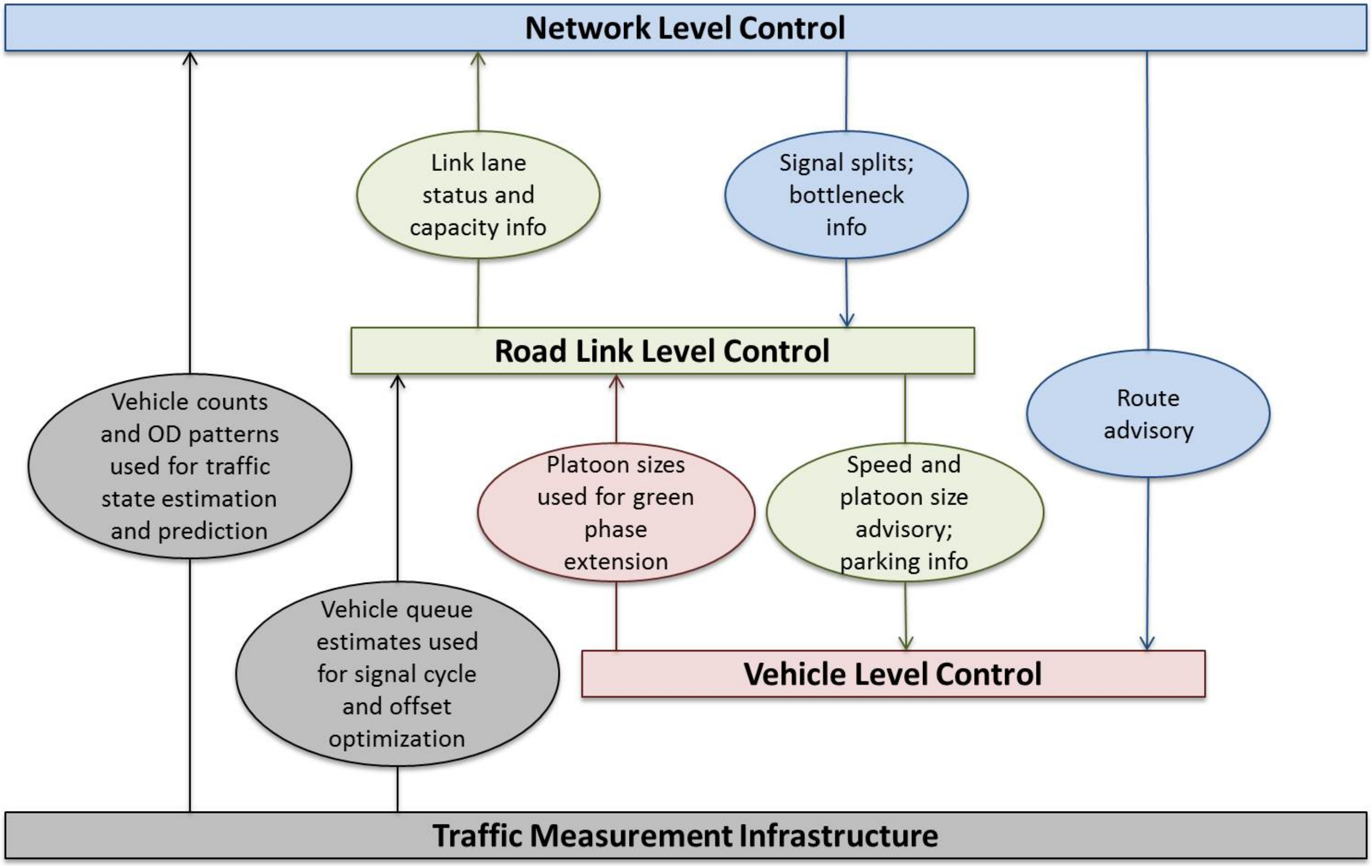
Cross-Layer Traffic Control

Goal: Making full use of existing infrastructure by coordinating network-level, road link-level and vehicle-level control actions.



NSF/DOT CPS Project "Traffic Operating System," Horowitz, Kurzhanskiy, Arcak, Varaiya

This Talk

Vignettes from vehicle- and road link-level interfacing:

1. Platoons at intersections and real traffic demonstration

   [Smith, Kim, Guanetti, Kurzhanskiy, Arcak, Borrelli, 2019]

2. Traffic light phase prediction and speed advisory

   [Burov, Kurzhanskiy, Arcak, in progress]

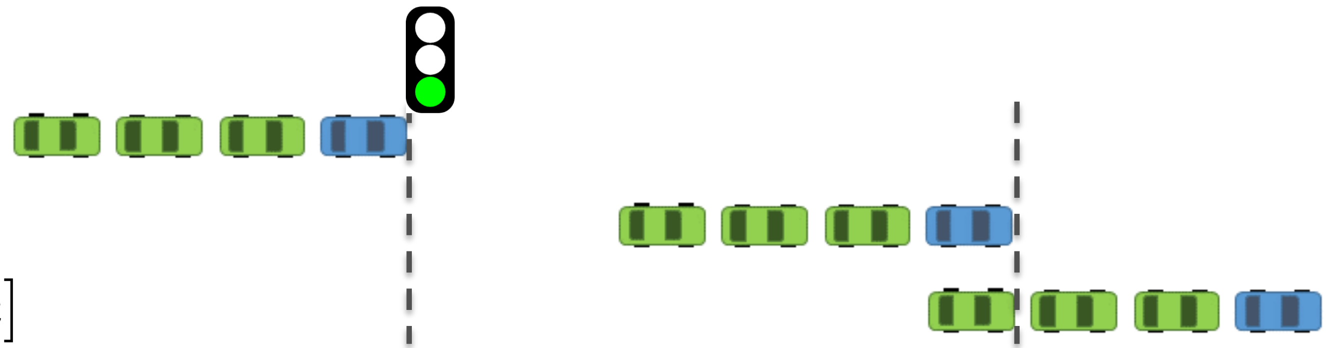
Platoons at Intersections

Dramatically increase intersection capacity by maintaining a small space gap during acceleration from rest.

$t = 0$

$t = t_L$

$t = t_3$ [sec]



$$\text{throughput} \approx 3600 \frac{3}{t_3 - t_L} \ \text{[vph]}$$

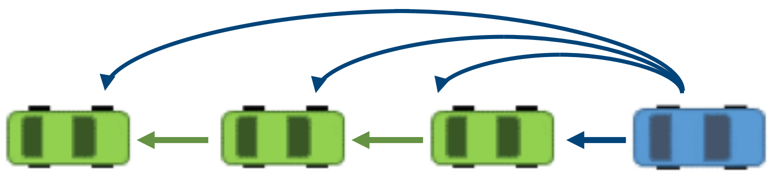
Platoons that average 0.95 sec. headway would *double* Highway Capacity Manual's estimate of 1900 vph [Lioris et al. 2017].

How can we achieve this while maintaining safety and comfort?

V2V Communication

Vehicles equipped with camera, radar, GPS, and Cooperative Adaptive Cruise Control enabled with DSRC.

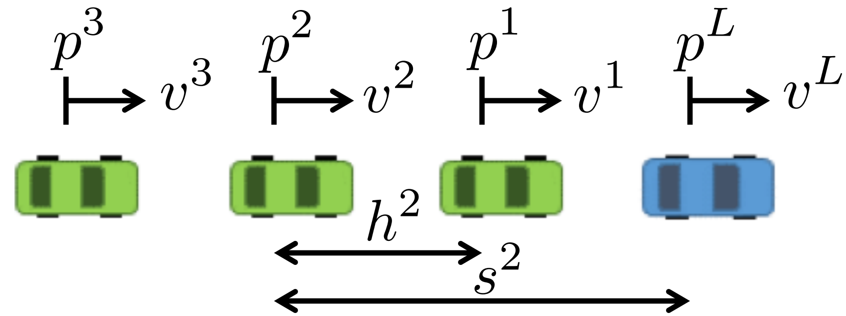
We use the predecessor-following / leader-information topology:



Messages contain timestamp, current position (leader) and velocity forecast (all vehicles):

$$m^L = [t_{sent};\ p^L(t|t);\ v^L(t|t);\ \ldots\ v^L(t+N_p|t)]$$
$$m^i = [t_{sent};\ v^i(t|t);\ \ldots\ \ v^i(t+N_p|t)]$$

Longitudinal Vehicle Model



Dynamical equations for vehicle *i* :

$$\left.\begin{aligned}
\dot{p}^i &= v^i, \\
\dot{s}^i &= v^L - v^i, \\
\dot{h}^i &= v^{i-1} - v^i, \\
\dot{v}^i &= \frac{1}{M}\left(\frac{T_w^i}{R_w} - F_f^i\right), \quad i = 1, \ldots, N-1, \\
F_f^i &= Mg(sin(\theta) + c_r cos(\theta)) + \frac{1}{2}\rho A c_x (v^i)^2
\end{aligned}\right\} \quad \dot{x}^i = f(x^i, u^i, w^i)$$

$w^i := [v^{i-1} \;\; v^L]$ treated as disturbance, with preview available from DSRC messages

Distributed MPC

MPC formulation to manage throughput/safety/comfort tradeoffs:

$$\min_{u(\cdot|t)} \quad J^i = \sum_{i=t}^{t+N_p} (s^i(k|t) - s^i_{des})^2 \qquad (1)$$

maintain desired distance to leader

$$+ \alpha \sum_{i=t}^{t+N_p-1} (u^i(k+1|t) - u^i(k|t))^2 \qquad (2)$$

penalty on jerk

$$\text{s.t.} \quad x^i(k+1|t) = A^i x^i(k|t) + B^i u^i(k|t) + E^i \hat{w}^i(k), \qquad (3)$$

dynamic model with disturbance preview

$$v_{min} \le v^i(k|t) \le v_{max}, \qquad (4)$$

velocity constraints

$$h_{min} \le h^i(k|t), \qquad (5)$$

headway constraint

$$u_{min} \le u^i(k|t) \le u_{max}, \qquad (6)$$

torque constraints

$$x^i(t|t) = \hat{x}^i(t), \qquad (7)$$

initialize model with current state

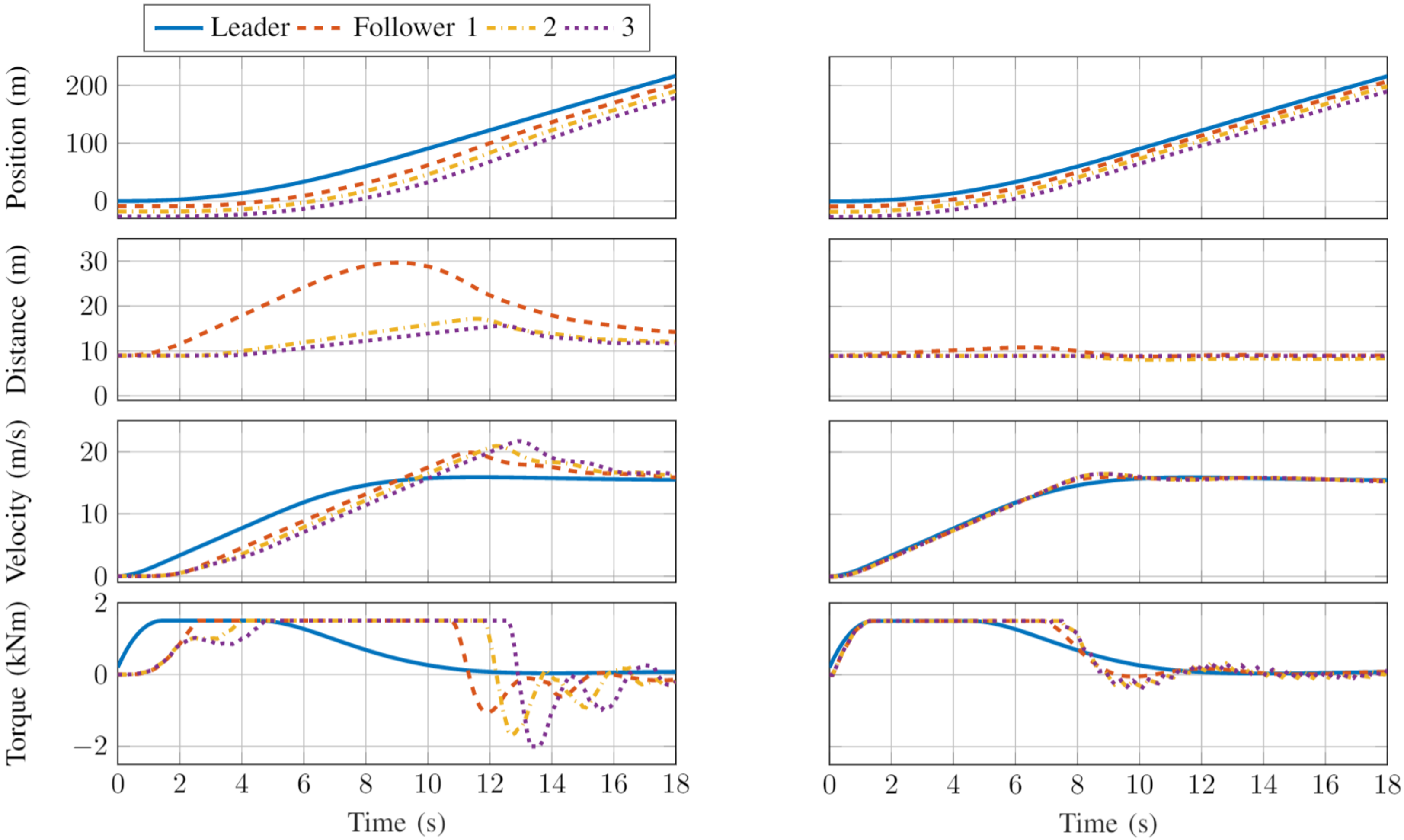
$$\forall k = t, \ldots, t + N_p - 1,$$

$$\begin{bmatrix} h^i(t+F|t) \\ v^i(t+F|t) \end{bmatrix} \in C(\hat{v}^{i-1}(t+F)). \qquad (8)$$

safety constraint if preceding vehicle were to brake t+F

Quadratic program solved online and control $u^i(t|t)$ applied.

Simulation Results



(a) Baseline: $F = 0$.

(b) V2V messages are fully trusted: $F = N_p$.

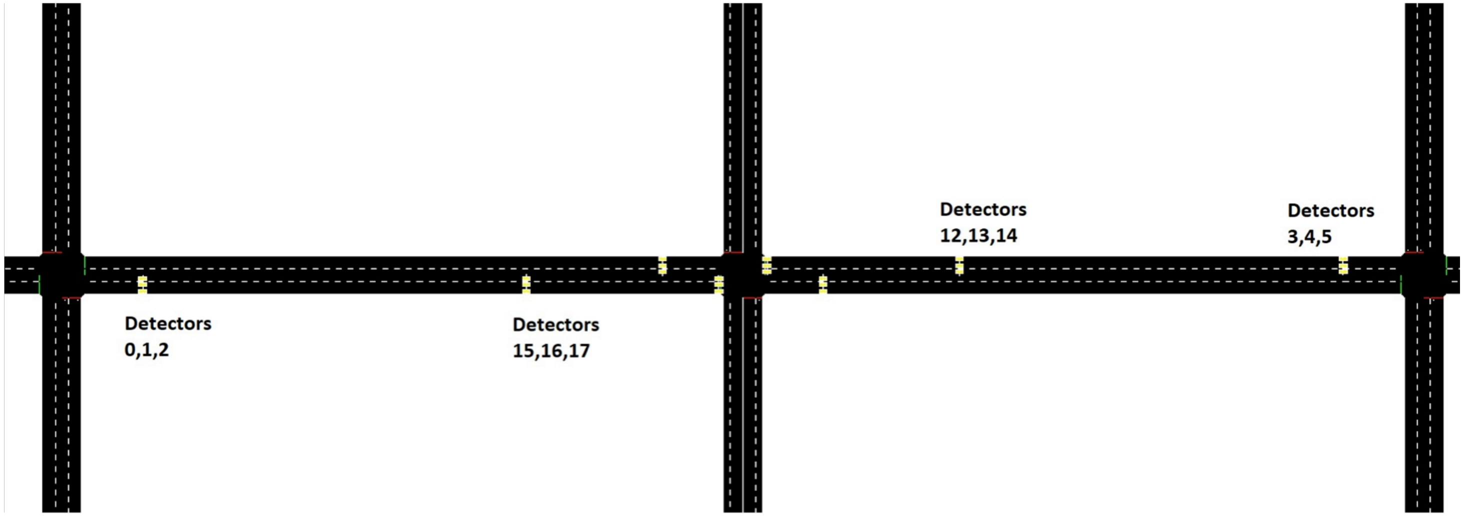
Transition to Practice

- Prototype
  - Implemented with YALMIP in MATLAB
  - Tested in Simulink
- Code-generated software
  - Custom QP solver built with cvxgen
  - Tested in Simulink
- Embedded Controller
  - Tested on Hyundai Ioniq
- Real traffic demonstration planned in Arcadia, CA. Preliminary tests conducted at Richmond Field Station of UC Berkeley.

CVXGEN

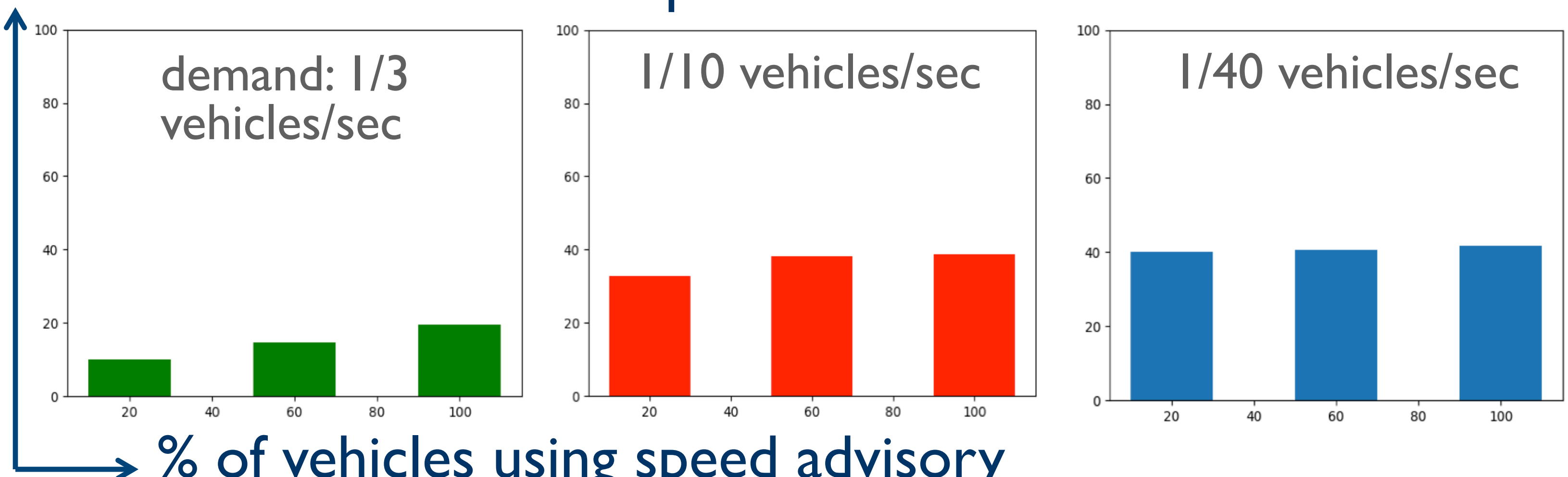
Phase Prediction and Speed Advisory

Adapt vehicle speed to green phase of *actuated* traffic lights to reduce fuel consumption and to improve progression quality.



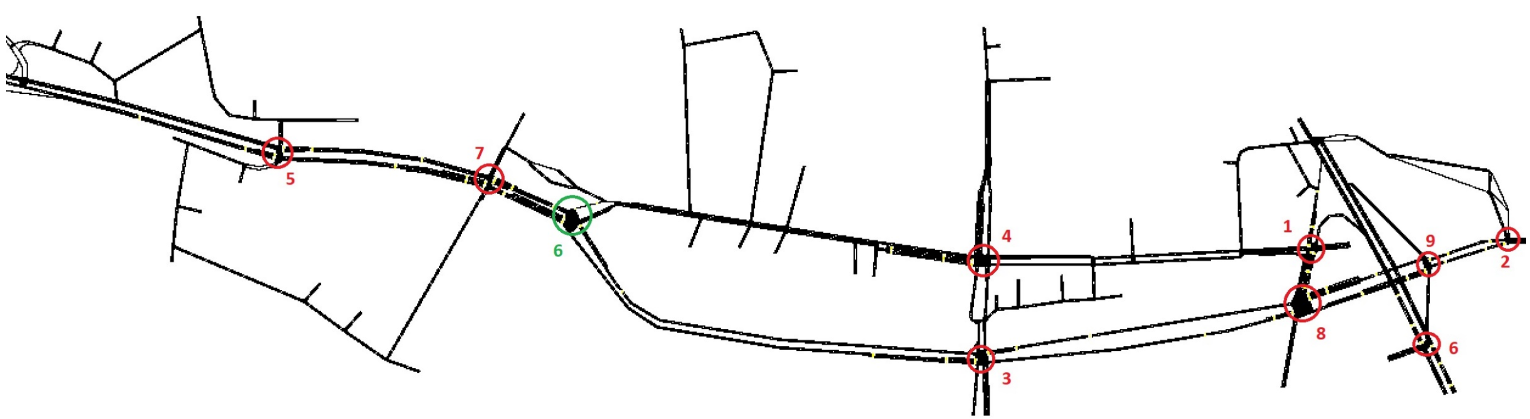
Road-side infrastructure uses speed of cars and time of crossing at advance detectors to predict whether green phase extension will be triggered. Vehicles receive this information via V2I comm. and select optimal speed profile.

% reduction in fuel consumption



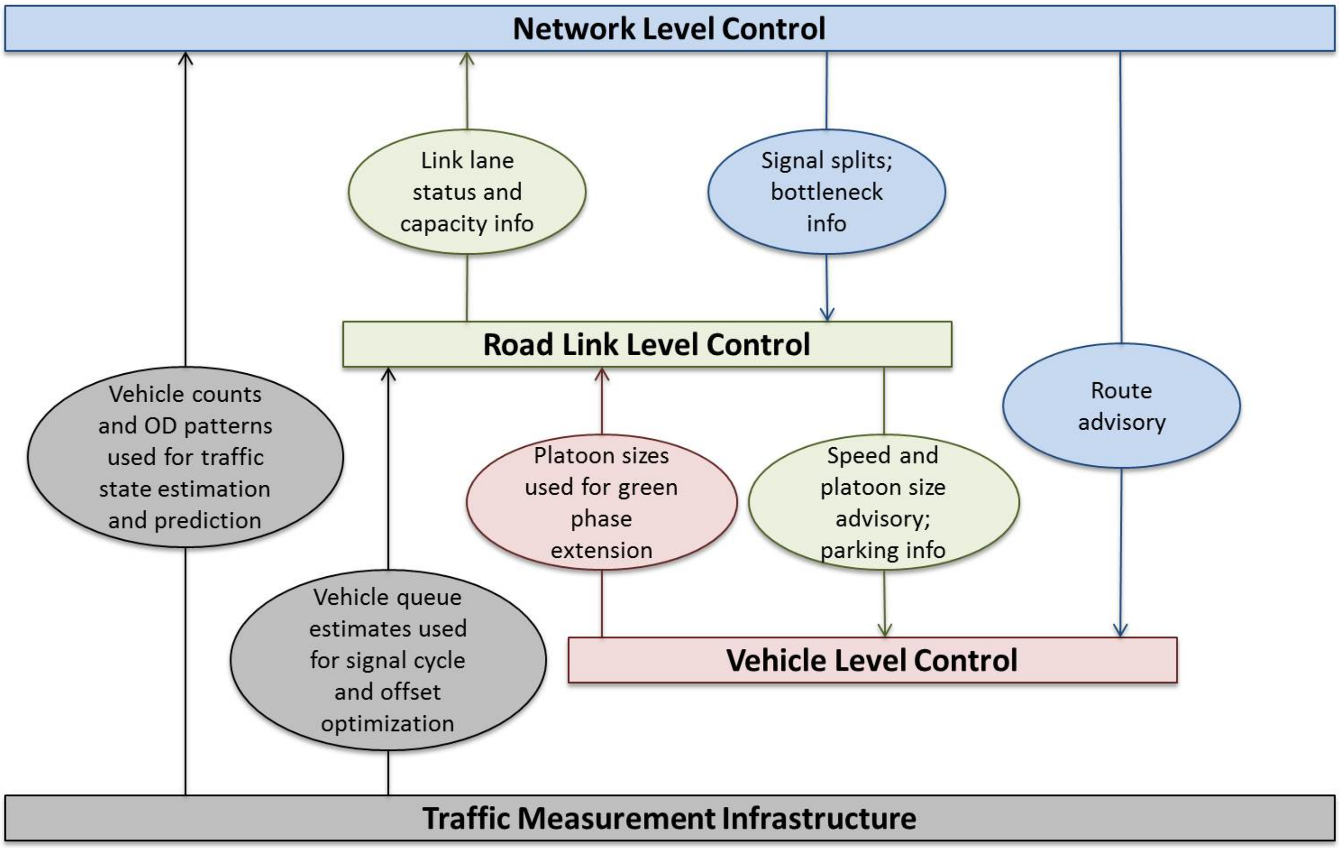
% of vehicles using speed advisory

Current work: simulation of network from Montgomery Co. with heterogeneous intersection geometries, phases, and vehicles.



Conclusions

Connected vehicle technology enables cross-layer traffic control and better utilization of infrastructure. Growing literature and opportunities for other instances of cross-layer control.



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