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.

Network Level Control
- Link lane status and capacity info
- Signal splits; bottleneck info

Road Link Level Control
- Platoon sizes used for green phase extension
- Speed and platoon size advisory; parking info
- Route advisory

Vehicle Level Control
- Vehicle counts and OD patterns used for traffic state estimation and prediction
- Vehicle queue estimates used for signal cycle and offset optimization

Traffic Measurement Infrastructure

NSF/DOT CPS Project “Traffic Operating System,” Horowitz, Kurzhanskiy, Arcak, Varaiya
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.

\[ t = 0 \]
\[ t = t_L \]
\[ t = t_3 \ [\text{sec}] \]

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 $i$:

\[
\begin{align*}
\dot{p}^i &= v^i, \\
\dot{s}^i &= v^L - v^i, \\
\dot{h}^i &= v^{i-1} - v^i, \\
\ddot{v}^i &= \frac{1}{M} \left( \frac{T_w^i}{R_w} - F_f^i \right), \quad i = 1, \ldots, N - 1, \\
F_f^i &= Mg \left( \sin(\theta) + c_r \cos(\theta) \right) + \frac{1}{2} \rho A c_x (v^i)^2
\end{align*}
\]

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

MPC formulation to manage throughput/safety/comfort tradeoffs:

\[
\min_{u(\cdot|t)} J_i = \sum_{i=t}^{t+N_p} (s_i^i(k|t) - s^i_{des})^2 \\
+ \sum_{i=t}^{t+N_p-1} (u^i(k+1|t) - u^i(k|t))^2
\]

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

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

\[
v_{min} \leq v^i(k|t) \leq v_{max},
\]

\[
h_{min} \leq h^i(k|t),
\]

\[
u_{min} \leq u^i(k|t) \leq u_{max},
\]

\[
x^i(t|t) = \hat{x}^i(t),
\]

\[
\forall k = t, \ldots, t + N_p - 1,
\]

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

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.
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.
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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