Traffic Flow Control in a Connected Environment

Petros Ioannou
Center for Advanced Transportation Technologies
METRANS University Transportation Center
University of Southern California
Los Angeles, CA, USA
Brief History

- Automated Highway System Program started in the 80’s ended with 1997 Demo. Platooning plus other technologies
- Replaced with IV initiative with vehicle safety as priority
- 2004, 2005, 2007 DARPA Challenge Competition
- Current: Autonomous Vehicles, 5 levels of Autonomy (Google Cars, Tesla, Uber etc)
- Efforts are to get rid of the driver when vehicles is the cause of congestion
Drag reduction: Fuel savings, lower pollution

\[ \Delta V^2 = \left( V_1 - V_2 \right)^2 \]

\[ \Delta V = V_1 - V_2 \]

Safety Objective: No vehicle should be put in a position it cannot handle
WHAT IS THE MAIN TRANSPORTATION PROBLEM?
This is what we usually see and experience
Transportation System for Moving Goods and People is far more complex
CURRENT TRANSPORTATION SYSTEM

• Nonlinear Dynamical System of interconnected systems
• Open Loop Most of the Time
• Limited ineffective feedback
• Lack of sensor data and connectivity

Consequences
• Congestion
• Inefficient utilization of infrastructure
• Safety
• Pollution
• Long travel times, High cost
• Unbalanced in time and space
Connectivity will Revolutionize Transportation

• Open loop operations will become more stable and robust via active feedback

• Information/data are crucial in optimizing processes and movements of people and goods

• Enhance coordination

• Vehicle to Infrastructure Connectivity is Proven Technology

• Private sector is moving faster to satisfy user needs
Traffic Management Control (TMC) System

Data Acquisition & Processing

Traffic Controller

Traffic System

Control Inputs

Output: Traffic Data

T0

T1

T2

TMC System

NSF Workshop June 8-9, 2019
Closing the loop with the Highway System

Speed, Location, OD, status (incident report)

Optimum speed limits, Lane Change, VSL Routing, Pricing

Ramp metering commands

Ramp Metering
MANETs For Lane Change Control and Collision Avoidance
Control of traffic at incidents and bottlenecks

- Highway congestions at bottlenecks is detrimental to traffic mobility, safety and environment
- Upstream drivers lack of information of bottleneck therefore blindly change lanes when traffic slows down

- Forced lane changes performed at vicinity of bottlenecks introduce capacity drop, which further harm the flow rate
- Appearance of trucks exacerbate the congestion condition
NO CONTROL  NO CONNECTIVITY
Modeling of Highway Bottleneck

Capacity drop

\[ q_b = \begin{cases} \nu_f \rho, & \rho \leq \rho_{d,c} \\ (1 - \epsilon) C_b, & \rho > \rho_{d,c} \end{cases} \]

- Capacity will drop when \( \rho > \rho_{d,c} \).
- Difficult to maintain maximum flow rate by controlling just the speed.
Design of Lane Change Controller to prevent last minute forced lane changes

Two Parts:
❖ Design of lane change control distance
  How far from incident should start recommending lane changes?
❖ Design of lane change control pattern
  What lane change recommendation should give in each lane?
Not a traditional control problem as the key variable is not time but space.
Design of Lane Change Controller based on an empirical model developed using simulation tests

Length of LC Control Segment:

\[ d_{LC} = \xi \cdot n \]

- \( n \): number of lanes closed
- \( \xi \): design parameter based on the demand and capacity
Effect of Lane Change Control
Effect of Lane Change Control

Without LC Control:
- Data points for $\rho_d \leq \rho_{d,c}$ fits the linear relation very well;
- Significant capacity drop occurs, $\epsilon \approx 0.16$
- Data points concentrate in high density area

With LC Control:
- No obvious capacity drop
- $\rho_d$ at $\rho_d > \rho_{d,c}$ is approximately linear with a negative
- Most data points scatter close to $\rho_d > \rho_{d,c}$
Protecting the Network
Variable Speed Limit Control

- If demand increases to the point that exceeds capacity of bottleneck then congestion will kick in. Need a control mechanism to protect the network.
- Provide speed recommendations upstream the bottleneck or incident in order to slow down the traffic flow to become close to the throughput of the bottleneck.
- Approach is implemented at various highways in Europe and US but in an adhoc way.
\[ \dot{\rho} = q_1 - q_2, \quad 0 \leq \rho(0) \leq \rho^j \]

where

\[
q_1 = \min\{d, C, w(\rho^j - \rho)\}
\]

\[
q_2 = \begin{cases} 
\min\{v_f \rho, w(\rho^j - \rho), (1 - \epsilon(\rho))C_d\}, & \text{if } C_d < C \\
\min\{v_f \rho, w(\rho^j - \rho), C_d\}, & \text{otherwise}
\end{cases}
\]

\[ v_f \rho_c = w(\rho^j - \rho_c) = w(\rho^j - \rho_e) = C \]

\[ 0 < \rho_c < \rho^j, \quad 0 < w < w, \quad v_f > 0 \]

\[ \epsilon(\rho) = \begin{cases} 
0 & \text{if } 0 \leq \rho \leq \frac{C_d}{v_f} \\
\epsilon_0 & \text{otherwise}
\end{cases} \]

Traffic Flow Model and Stability Analysis

Let \( I = (C_d, C, d) \) be the state of the network and \( \Omega \) be the set of feasible values of \( I \) with \( d \geq 0, C_d > 0, C > 0 \). All possible relationships between \( C_d, C \) and \( d \) are described by the tree diagram below:
Equilibrium Points when Inflow = Outflow i.e. $q_1 = q_2 \implies \dot{\rho} = 0$
Theorem 1. For constant but otherwise arbitrary demand $d$, we have the following results:

a) Let $I \in \Omega_1$. Then $\forall \rho(0) \in [0, \rho^j]$, $\rho(t)$ converges exponentially fast to $\frac{d}{v_f}$.

b) Let $I \in \Omega_2$. Then
   - $\forall \rho(0) \in [0, \frac{C_d}{v_f}]$, $\rho(t)$ converges exponentially fast to $\frac{d}{v_f} = \frac{(1-\epsilon_0)C_d}{v_f}$.
   - $\forall \rho(0) \in (\frac{C_d}{v_f}, \rho^j - \frac{d}{v_f}]$, $\rho(t) = \rho(0), \forall t \geq 0$.
   - $\forall \rho(0) \in (\rho^j - \frac{d}{w}, \rho^j]$, $\rho(t)$ converges exponentially fast to $\rho^j - \frac{d}{w} = \rho^j - \frac{(1-\epsilon_0)C_d}{w}$.

c) Let $I \in \Omega_3$. Then
   - $\forall \rho(0) \in [0, \frac{C_d}{v_f}]$, $\rho(t)$ converges exponentially fast to $\frac{d}{v_f}$.
   - $\forall \rho(0) \in (\frac{C_d}{v_f}, \rho^j]$, $\rho(t)$ converges exponentially fast to $\rho^j - \frac{(1-\epsilon_0)C_d}{w}$.

d) Let $I \in \Omega_4$. Then $\forall \rho(0) \in [0, \rho^j]$, $\rho(t)$ converges exponentially fast to $\rho^j - \frac{(1-\epsilon_0)C_d}{w}$.

e) Let $I \in \Omega_5$. Then $\forall \rho(0) \in [0, \rho^j]$, $\rho(t)$ converges exponentially fast to $\frac{\min\{d,C\}}{v_f}$. 
Variable Speed Limit (VSL) Control
Density Model

\[ \dot{\rho} = q_1 - q_2, \quad 0 \leq \rho(0) \leq \rho^j \]

\[ q_1 = \min\{d, \frac{vw\rho^j}{v+w}, C, w(\rho^j - \rho)\} \]

\[ q_2 = \min\{v_f\rho, \tilde{w}(\rho^j - \rho), 1 - \epsilon(\rho)C_d\} \]

VSL Controller

\[ \bar{v}_1 = \frac{w[q_2 - \lambda(x + \delta_1)]}{w\rho^j - [q_2 - \lambda(x + \delta_1)]} \]

\[ \bar{v}_2 = \frac{w(q_2 - \lambda x)}{w\rho^j - (q_2 - \lambda x)} \]

\[ v_t = \text{med}\{0, \bar{v}_1, v_f\} \]

\[ v = \begin{cases} 
  v_1 & \text{if } \rho(0) > \frac{C_d}{v_f} \text{ and } \rho(t) > \frac{C_d}{v_f} - \delta_2 \\
  v_2 & \text{if } \rho(0) > \frac{C_d}{v_f} \text{ and } \rho(t) = \frac{C_d}{v_f} - \delta_2 \\
  v_2 & \text{if } \rho(0) \leq \frac{C_d}{v_f} \text{ and } \rho(t) \leq \frac{C_d}{v_f} 
\end{cases} \]

where \( x = \rho - \frac{C_d}{v_f} \), and

\[ 0 < \delta_2 < \delta_1 < \frac{C_d}{v_f}, \quad 0 < \lambda < \frac{v_f w \rho^j}{C_d} \]
Main Theorem
The proposed VSL Controller guarantees that densities converge exponentially to a single equilibrium point

\[ \rho^* = \frac{\min[d, C_d]}{v_f} \]

that corresponds to maximum possible flow and speed under any demand and capacity constraints.

Proof: based on simple Lyapunov stability arguments
\[ d < (1 - \varepsilon_0) \times C_d \]
\[ d = (1 - \varepsilon_0) \times C_d \]

**Ω2 Open-loop**

**Closed-loop**
\( \Omega_3 \) Open-loop

\[(1 - \varepsilon_0) \cdot C_d < d \leq C_d\]
\[ C_d < d < C \]
Why it Works: Less for More  https://www.youtube.com/watch?v=9QwPfe-_T7s
\[ \dot{\rho}_i = q_i - q_{i+1}, \quad 0 \leq \rho_i(0) \leq \rho^j, \text{ for } i = 1, 2, \ldots, N \]

\[
q_1 = \min \{d, \frac{v_0 w \rho^j}{v_0 + w}, \frac{v_1 w \rho^j}{v_1 + w}, w(\rho^j - \rho_1)\}
\]

\[
q_i = \min \{\frac{v_{i-1} \rho_{i-1}}{v_{i-1} + w}, \frac{v_i w \rho^j}{v_i + w}, w(\rho^j - \rho_i)\}, \quad i = 2, 3, \ldots, N - 1
\]

\[
q_N = \min \{\frac{v_{N-1} w \rho^j}{v_{N-1} + w}, C, w(\rho^j - \rho_N)\}
\]

\[
q_{N+1} = \min \{v_f \rho_N, (1 - \epsilon(\rho_N))C_d, \tilde{w}(\tilde{\rho}^j - \rho_N)\}
\]
Numerical Simulation

Simulation Setup:

1. Simulation Network:
   16km-long southbound segment of I-710 freeway in California, whose normal capacity without an accident is about 6800 veh/h.

2. Incident Scenarios:
   We construct accident scenarios with different accident durations

<table>
<thead>
<tr>
<th>Scenario No.</th>
<th>Incident Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30 min</td>
</tr>
<tr>
<td>2</td>
<td>10 min</td>
</tr>
<tr>
<td>3</td>
<td>Not Removed</td>
</tr>
</tbody>
</table>

3. Monte Carlo Simulation
   10 sets of Monte Carlo simulation for each scenario in microscopic simulations.
- Traffic states can be stabilized in a small region for different demand levels
- Density stops increasing when demand higher than the capacity
- Flow speed decreases when density close to the critical value
## Performance

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Control Improvements for considered scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Time Spent in Network</td>
<td>10-15%</td>
</tr>
<tr>
<td>Number of Stops</td>
<td>80-90%</td>
</tr>
<tr>
<td>Number of Lane Changes</td>
<td>6-10%</td>
</tr>
<tr>
<td>NOx</td>
<td>6-7%</td>
</tr>
<tr>
<td>CO2</td>
<td>7-8%</td>
</tr>
<tr>
<td>Fuel</td>
<td>7-8%</td>
</tr>
<tr>
<td>PM25</td>
<td>4-7%</td>
</tr>
</tbody>
</table>
Coordination and connectivity in multimodal: Co-Simulation Optimization Control Approach

Transportation Network

Network Simulation Models

Network Data

Final Decision

Controller

Optimization

Stopping Criteria

Network states

NSF CPS Synergy: Cyber Physical Regional Freight Transportation System
Conclusions

- Connectivity (V to V and V to I) is a key technology in achieving transportation efficiency
- Connectivity will generate vital information and provide missing data that are necessary for effective control and optimization designs
- Vehicle automation, self driving vehicles will face the major challenge of Safety
- The main causes of congestion are too many vehicles. Getting rid of the driver and keeping the vehicle is unlikely to reduce congestion
- Congestion is a system level problem. The system is dynamical and feedback control and optimization are important tools to make it stable, robust and efficient
THANK YOU