Traffic Flow Control in a Connected Environment

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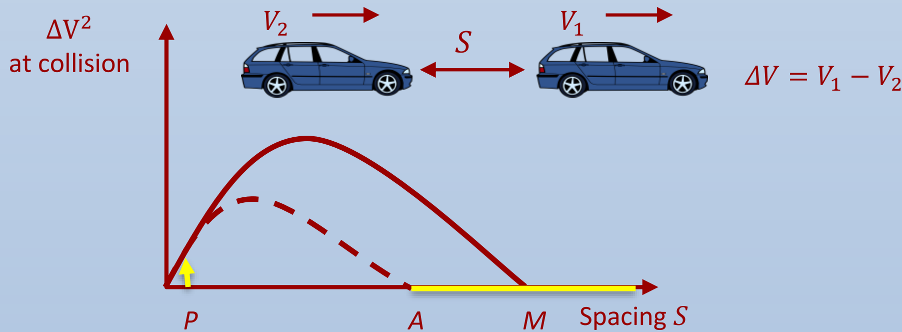
Brief History

- **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**

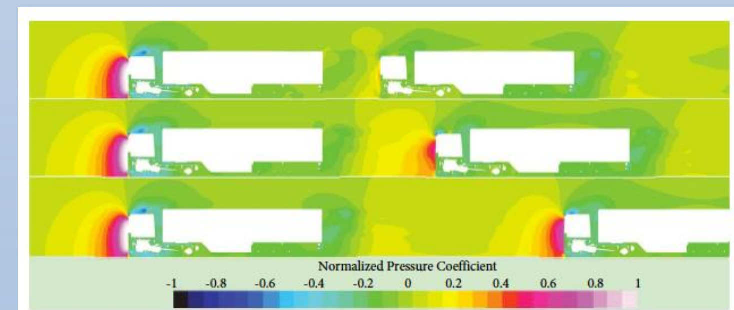
Vehicle Control Safety and Platooning



P: Platoon spacing (1 meter)

A: Automated M: Manual; $Capacity \propto \frac{1}{S}$

Drag reduction: Fuel savings, lower pollution



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

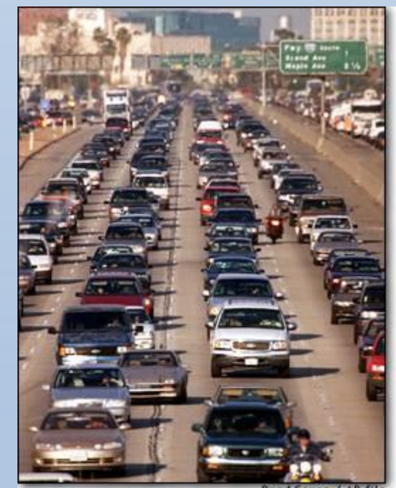
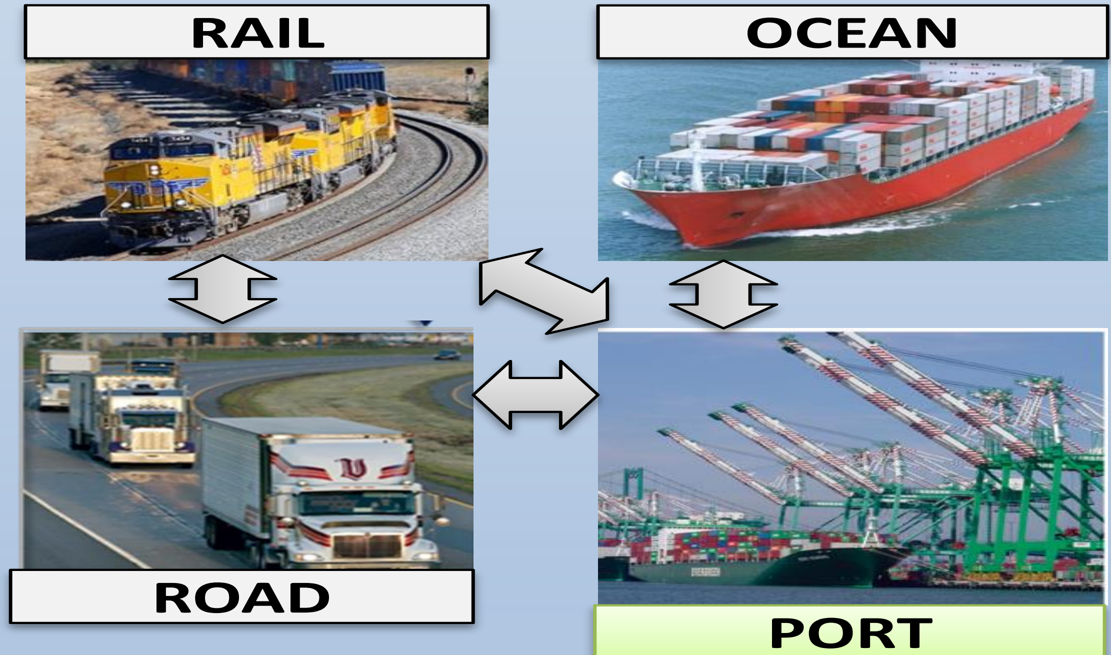


Image from www.msnbc.com

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

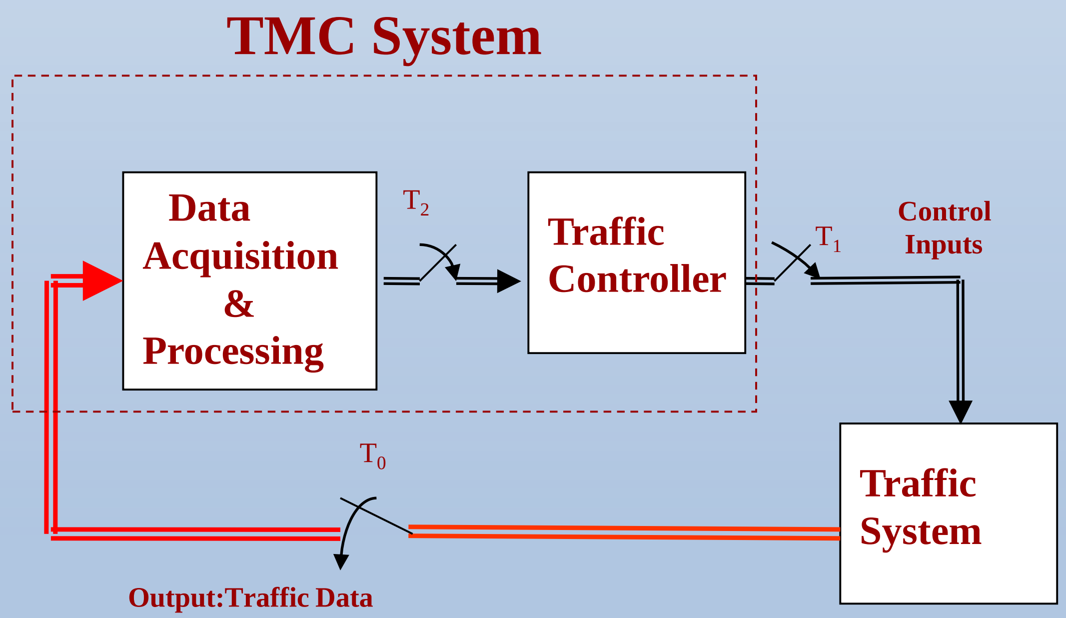
<u>Consequences</u>

- Congestion
- Inefficient utilization of infrastructure
- Safety
- Pollution
- Long travel times, High cost
- Unbalanced in time and space

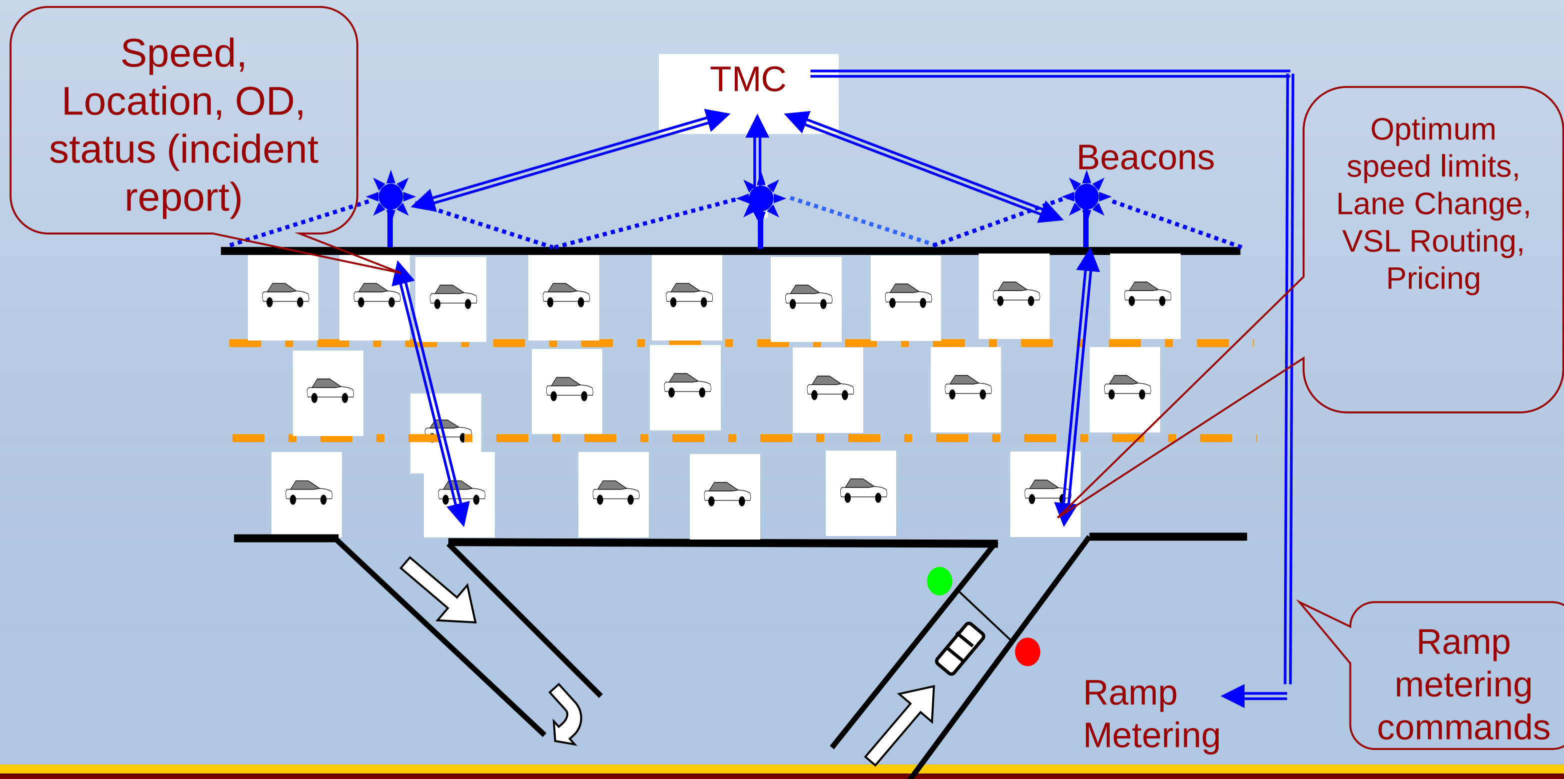
Connectivity will Revolutionize Transportation

- **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

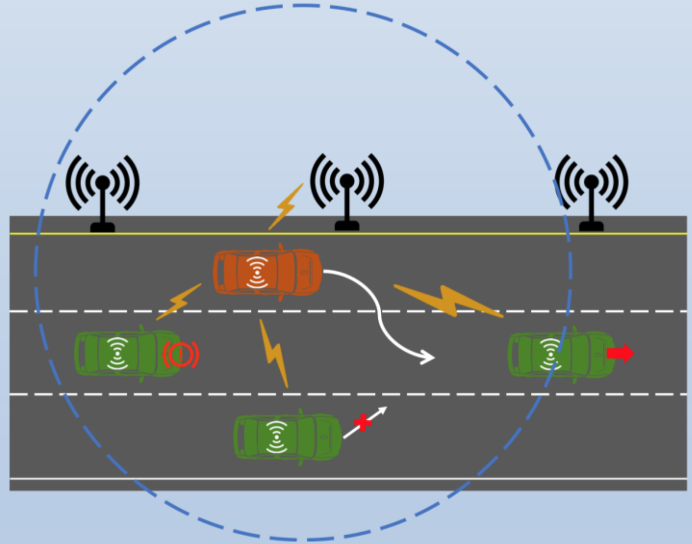
Traffic Management Control (TMC) System

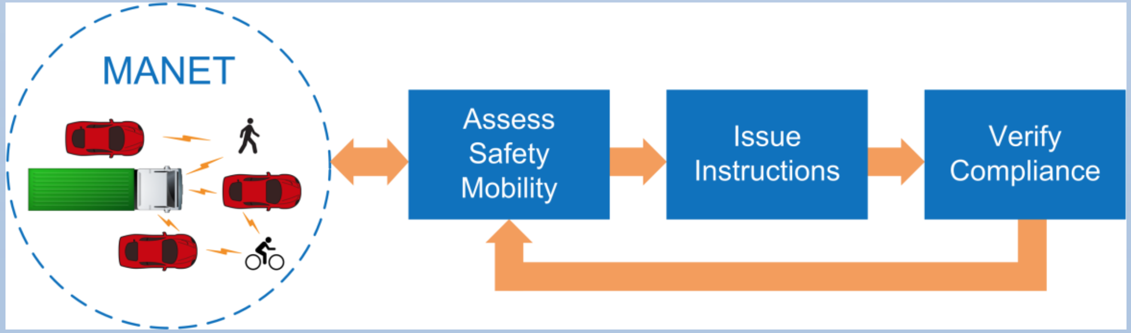


Closing the loop with the Highway System



MANETs For Lane Change Control and Collision Avoidance





Control of traffic at incidents and bottlenecks

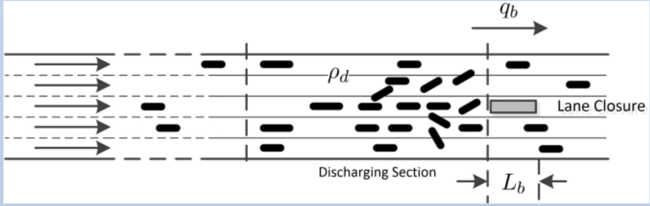
- Highway congestions at bottlenecks is detrimental to **traffic mobility, safety and environment**
- Upstream drivers lack of information of bottleneck therefore **blindly change lanes** when traffic slows down

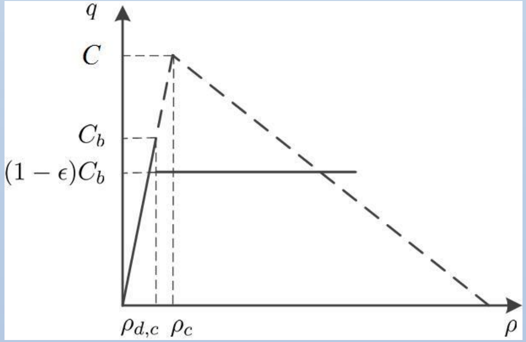
- **Forced lane changes** performed at vicinity of bottlenecks introduce **capacity drop**, which further harm the flow rate
- Appearance of trucks exacerbate the congestion condition

NO CONTROL NO CONNECTIVITY

Modeling of Highway Bottleneck

Capacity drop





$$q_b = \begin{cases} v_f \rho \;, & \rho \le \rho_{d,c} \\ (1-\epsilon)C_b, & \rho > \rho_{d,c} \end{cases}$$

- 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.

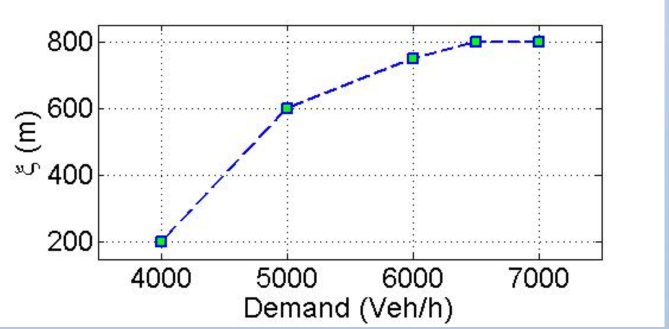
Design of Lane Change Controller based on an empirical model developed using simulation tests

Length of LC Control Segment:

$$d_{LC} = \xi \cdot n$$

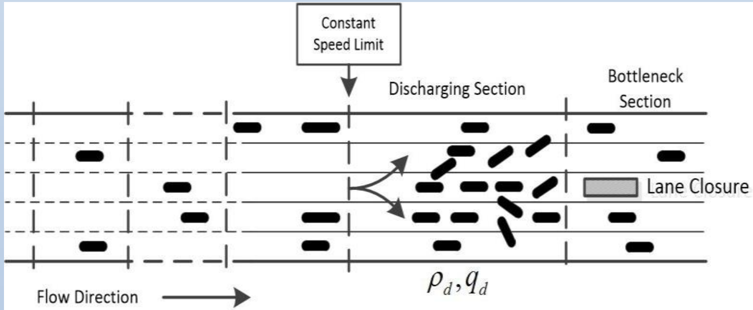
n: number of lanes closed

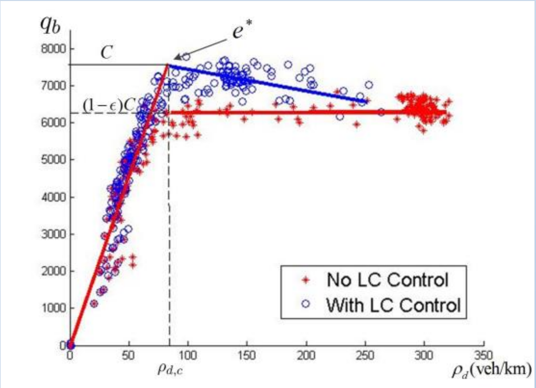
ξ: design parameter based on the demand and capacity



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

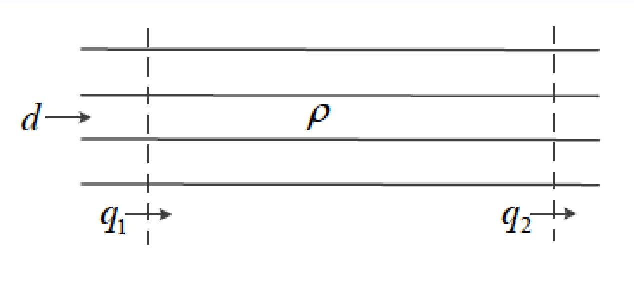
With LC Control:

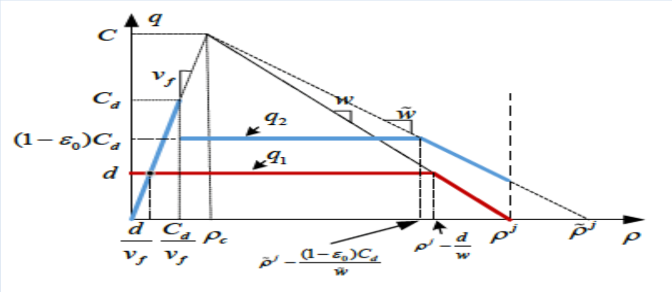
- No obvious capacity drop
- ρ_d at $\rho_d > \rho_{d,c}$ is approximately linear with a negative
- Most data points scatter close to $\rho_d > \rho_{d,c}$

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





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

where

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

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

$$v_f\rho_c = w(\rho^j - \rho_c) = \tilde{w}(\tilde{\rho}^j - \rho_c) = C$$

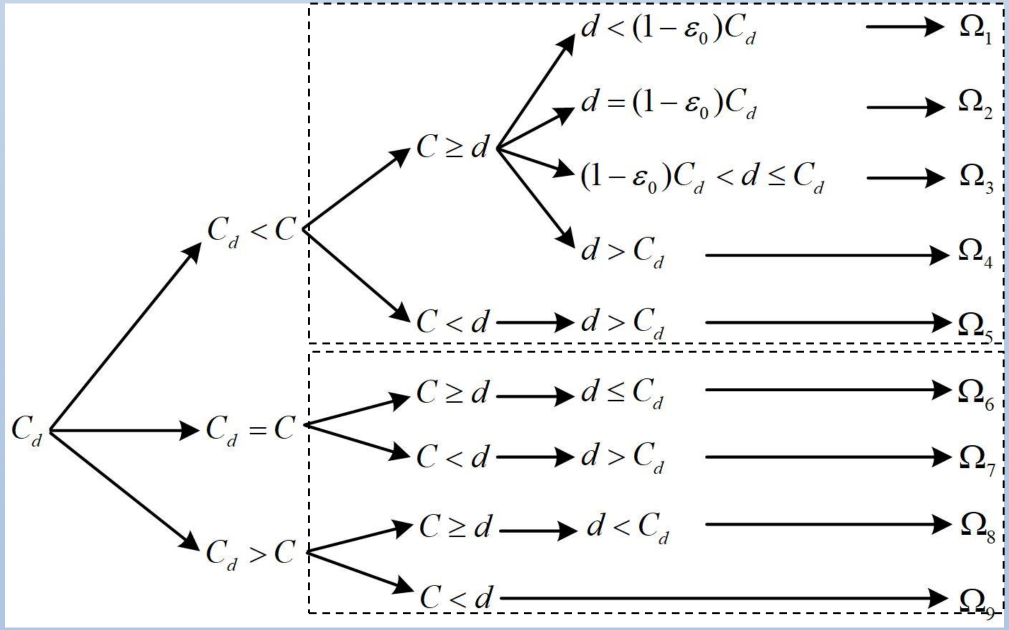
$$0 < \rho_c < \rho^j, 0 < \tilde{w} < w, v_f > 0$$

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

1.Carlos F Daganzo. The cell transmission model: A dynamic representation of highway track consistent with the hydrodynamic theory. *Transportation Research Part B: Methodological*, 28(4):269-287, 1994.

Traffic Flow Model and Stability Analysis

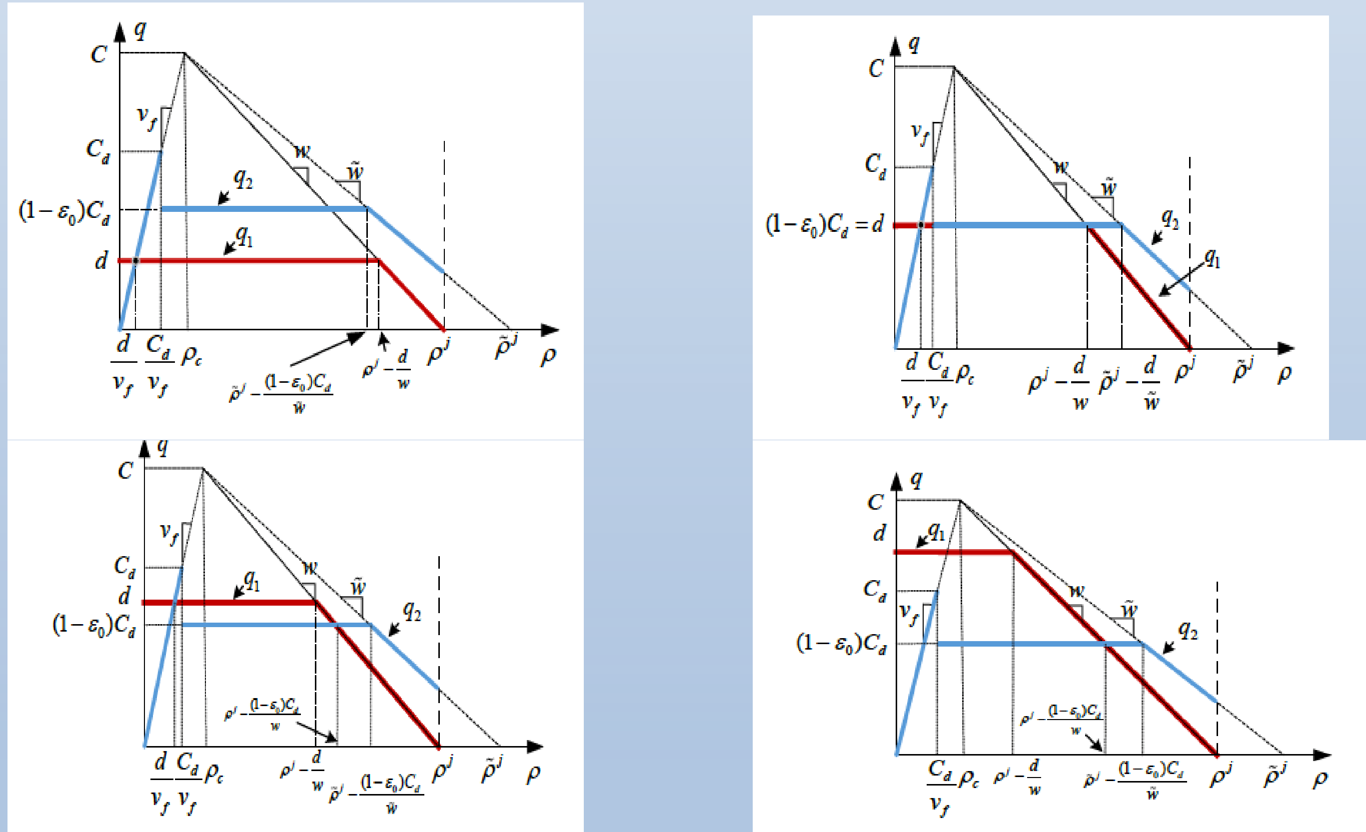
Let $I = (C_d, C, d)$ be the state of the network and Ω be the set of feasible values of I with $d \geq 0, C_d > 0, C > 0$. All possible relationships between C_d, C and d are described by the tree diagram below:



Capacity Drop

No Capacity Drop

Equilibrium Points when Inflow = Outflow i.e. $q_1 = q_2 \rightarrow \dot{\rho} = 0$



Variable Speed Limit Control

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* $\rho^j - \frac{d}{w} = \rho^j - \frac{(1-\epsilon_0)C_d}{w}$.

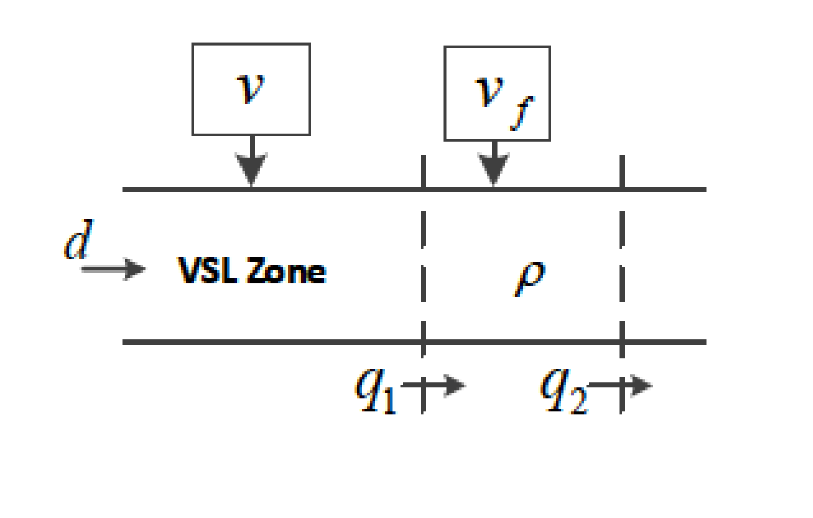
c) *Let $I \in \Omega_3$. Then*

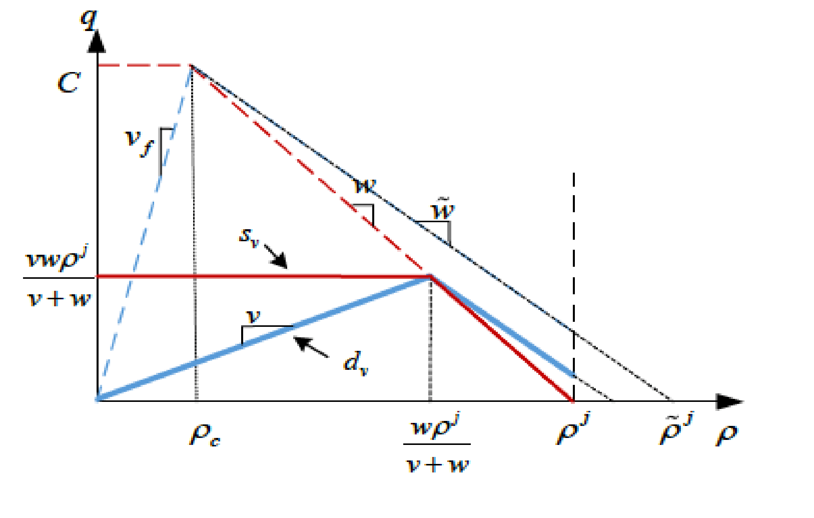
- $\forall \rho(0) \in [0, \frac{C_d}{v_f}]$, $\rho(t)$ *converges exponentially fast to* $\frac{d}{v_f}$.
- $\forall \rho(0) \in (\frac{C_d}{v_f}, \rho^j]$, $\rho(t)$ *converges exponentially fast to* $\rho^j - \frac{(1-\epsilon_0)C_d}{w}$.

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

$$\dot{\rho} = q_1 - q_2,\ 0 \le \rho(0) \le \rho^j$$

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

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

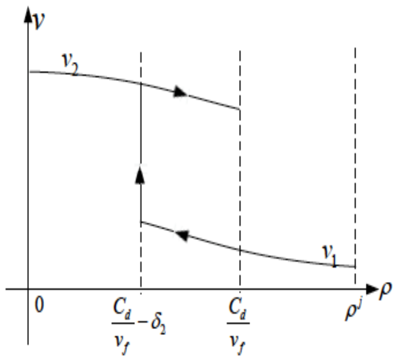
VSL Controller

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

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

$$v_i = \operatorname{med}\{0, \bar{v}_i, v_f\}$$

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



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

$$0 < \delta_2 < \delta_1 < \frac{C_d}{v_f},\ 0 < \lambda < \frac{v_f w \rho^j}{C_d}$$

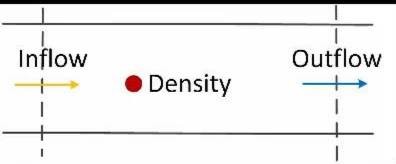
Main Theorem

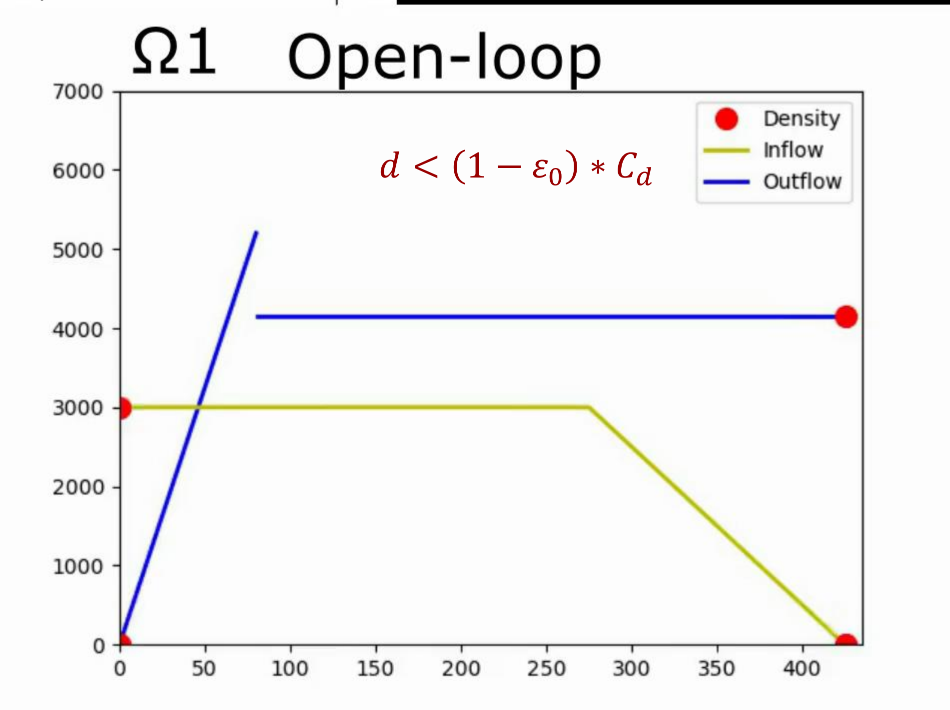
The proposed VSL Controller guarantees that densities converge exponentially to a single equilibrium point

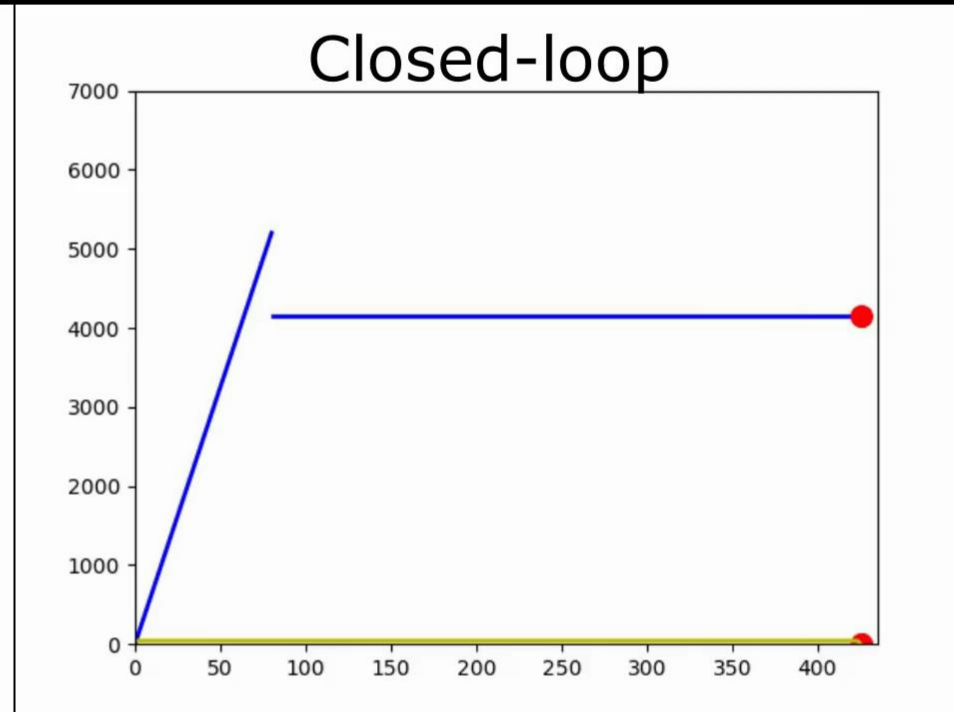
$$\rho^* = \frac{\min[d, C_d]}{v_f}$$

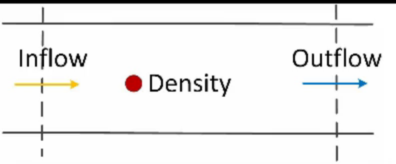
that corresponds to maximum possible flow and speed under any demand and capacity constraints.

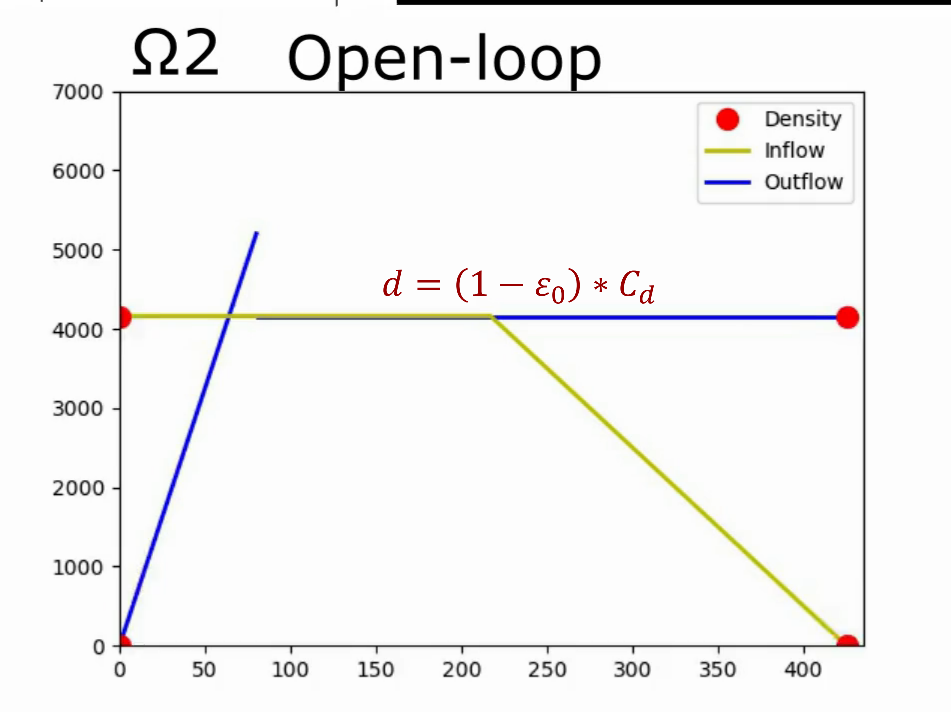
Proof: based on simple Lyapunov stability arguments

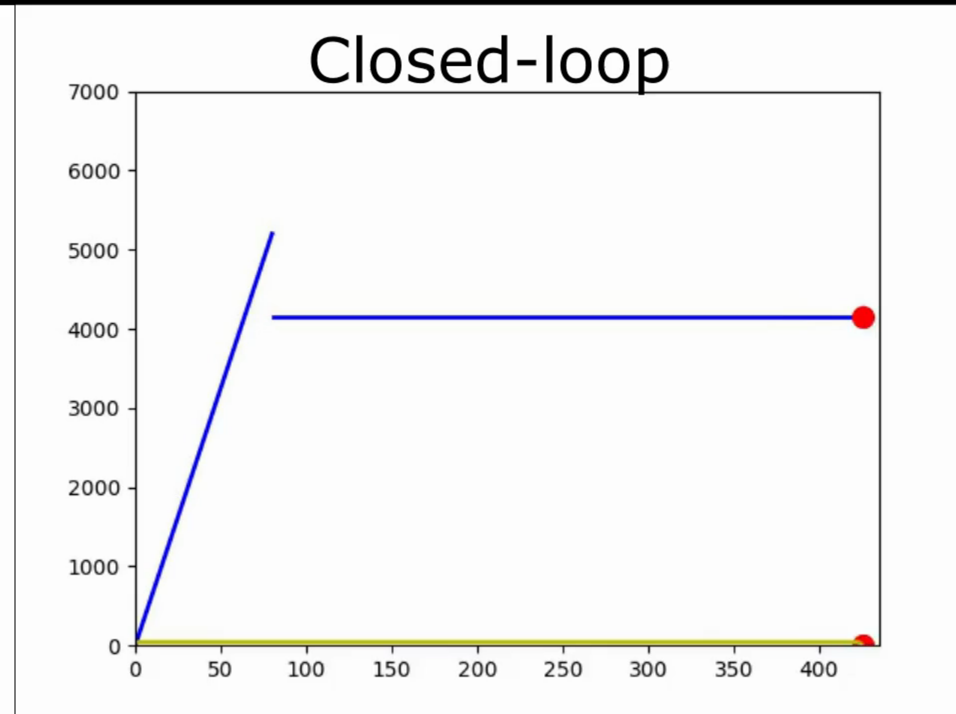

Inflow
Density
Outflow


Ω1 Open-loop
$d < (1 - \varepsilon_0) * C_d$
Density
Inflow
Outflow
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400


Closed-loop
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400


Inflow
Density
Outflow


Ω2 Open-loop
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400
Density
Inflow
Outflow
$d = (1 - \varepsilon_0) * C_d$


Closed-loop
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
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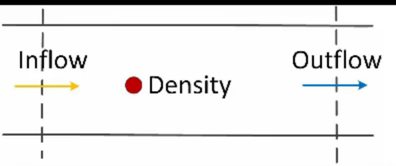
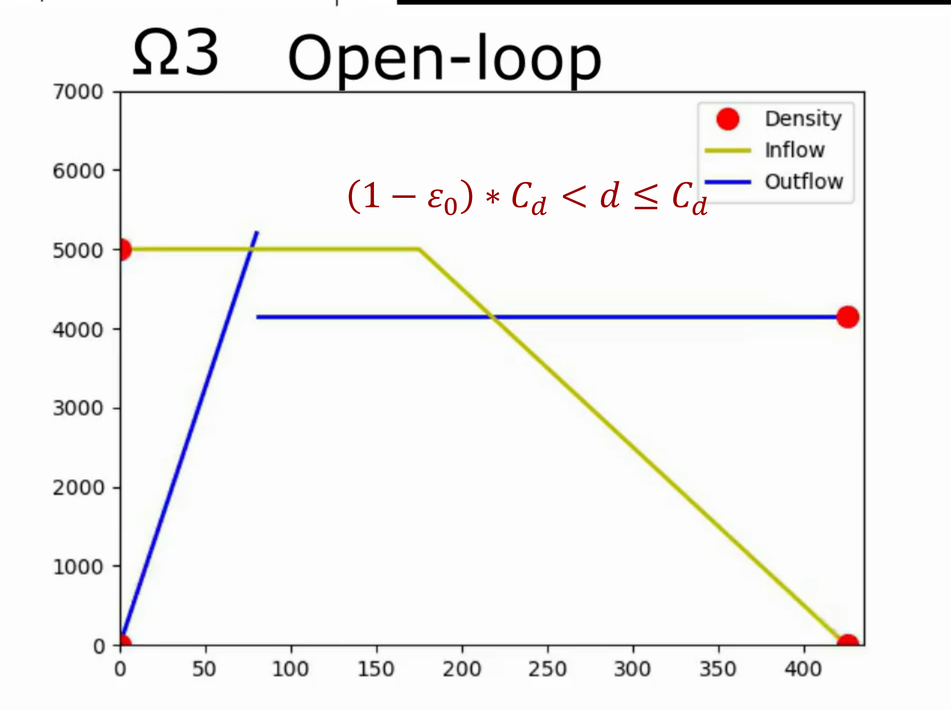
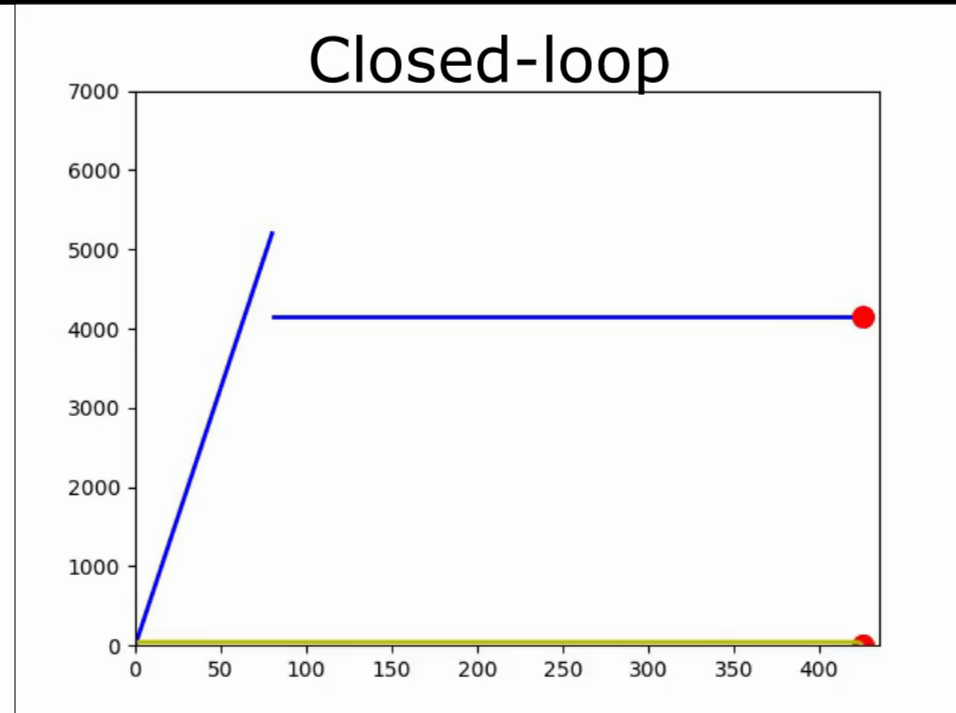
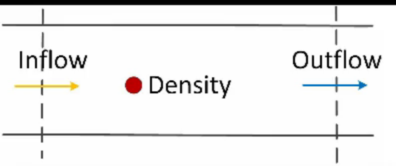
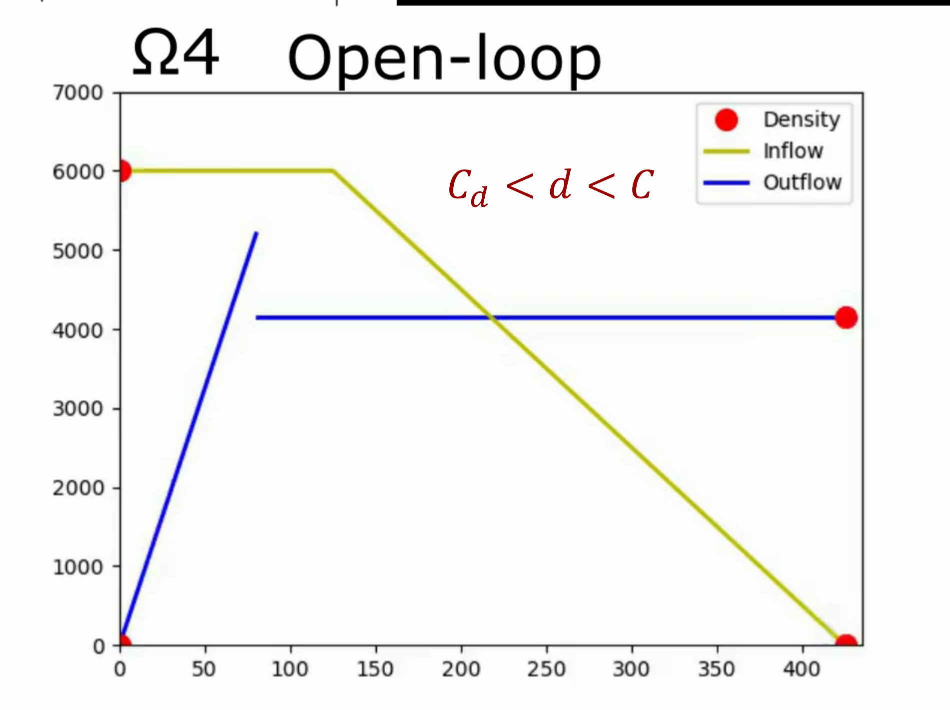
250
300
350
400

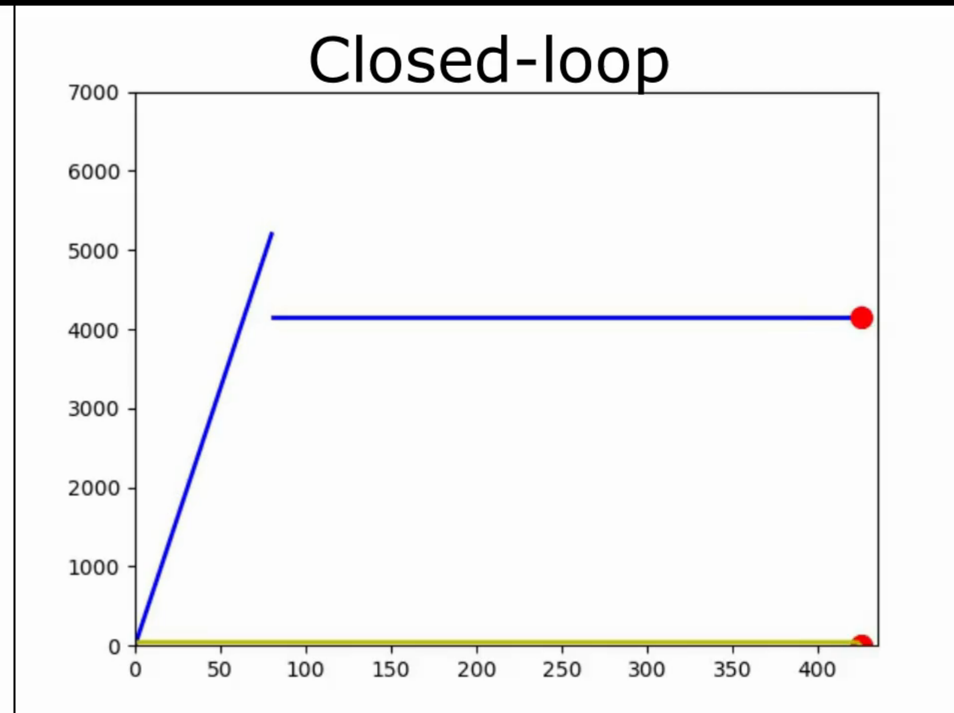

Inflow
Density
Outflow


Ω3 Open-loop
Density
Inflow
Outflow
$(1-\varepsilon_0) * C_d < d \leq C_d$


Closed-loop


Inflow
Density
Outflow


Ω4 Open-loop
$C_d < d < C$
Density
Inflow
Outflow
7000
6000
5000
4000
3000
2000
1000
0
0 50 100 150 200 250 300 350 400


Closed-loop
7000
6000
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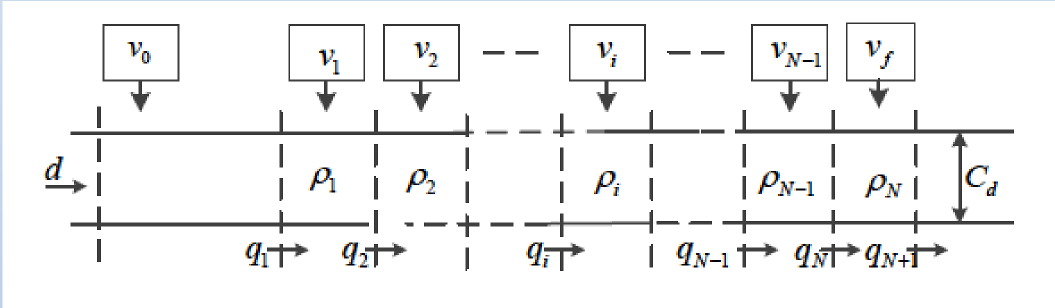
0 50 100 150 200 250 300 350 400

Why it Works: Less for More https://www.youtube.com/watch?v=9QwPfe-_T7s

Multiple Sections



$$\dot{\rho}_i = q_i - q_{i+1}, 0 \le \rho_i(0) \le \rho^j, \text{for } i = 1, 2, ..., N$$

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

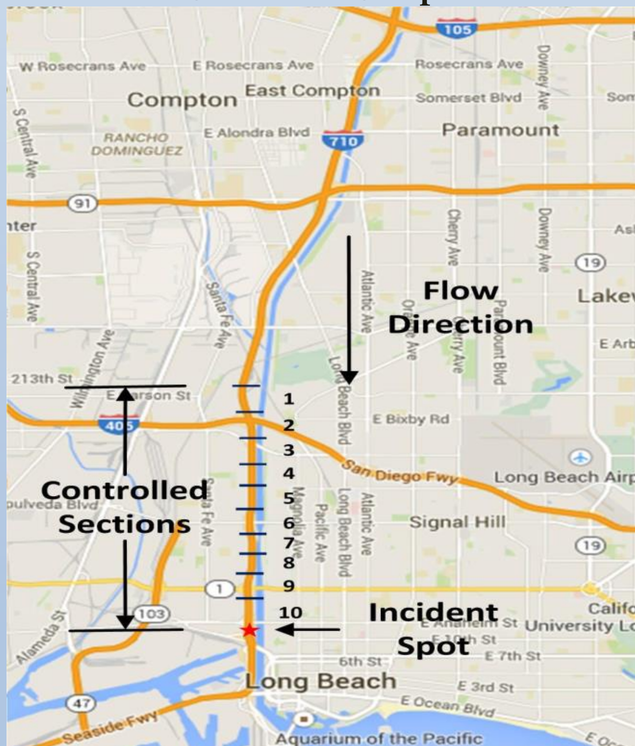
$$q_i = \min\{v_{i-1}\rho_{i-1}, \frac{v_{i-1} w \rho^j}{v_{i-1} + w}, \frac{v_i w \rho^j}{v_i + w}, w(\rho^j - \rho_i)\}, i = 2, 3, ..., N-1$$

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

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

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

Scenario No.	Incident Duration
1	30 min
2	10 min
3	Not Removed

3.
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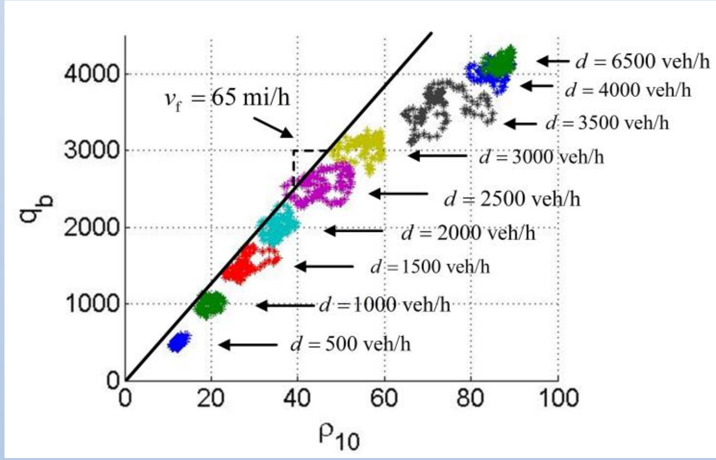
Fundamental Diagram under Control

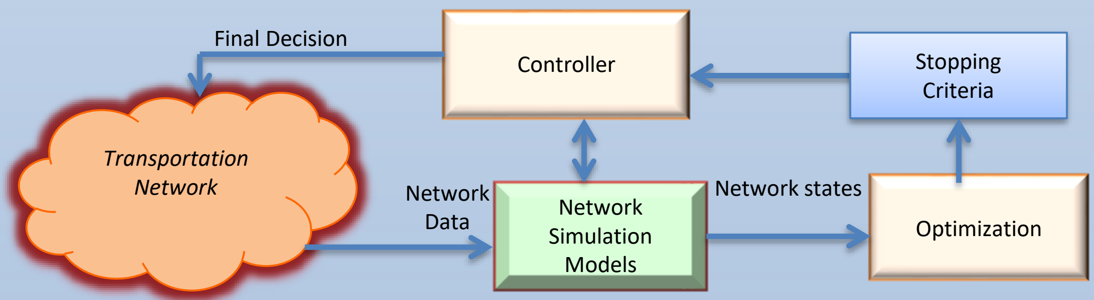


- Traffic states can be stabilized in a small region for different demand levels
- Density stops increasing when demand higher than the capacity
- Flow speed decreases when density close to the critical value

Performance

Criteria	Control Improvements for considered scenarios
Total Time Spent in Network	10-15%.
Number of Stops	80-90%
Number of Lane Changes	6-10%
NOx	6-7%
CO2	7-8%
Fuel	7-8%
PM25	4-7%

Coordination and connectivity in multimodal:
Co-Simulation Optimization Control Approach



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