Traffic Control Systems Security: Coordinated Ramp Metering Attacks

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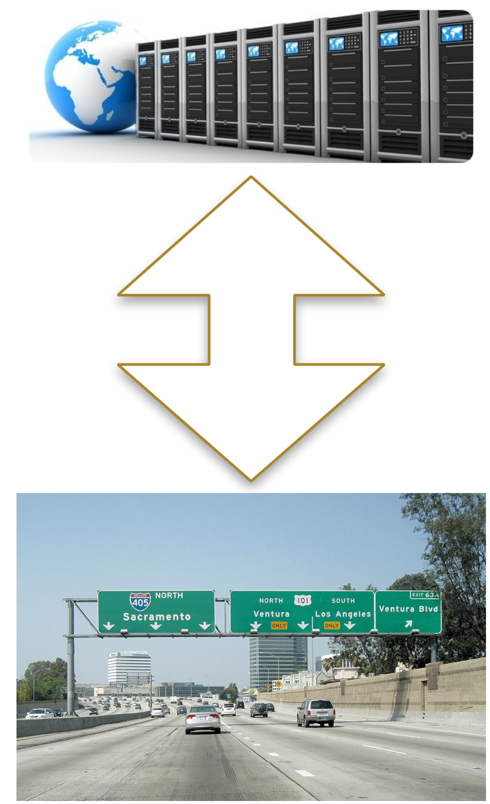
Overview of Talk

- Traffic Control Infrastructure
  - Actual Attack Examples
- SmartRoads: Traffic/Cybersecurity Testbed
- Coordinated Ramp Metering Attacks
  - Optimal Control
  - Multi-objective Optimization
- **Attack Examples**
  - Aiding a fleeing vehicle
  - Creating precise congestion patterns



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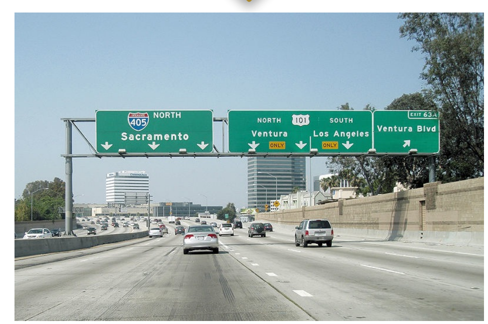
SmartRoads: Cyber-physical Security on Traffic Networks

- Traffic management has two components:
  - **Physical** sensors and traffic lights
  - **Virtual** control and estimation algorithms
- **Compromise** of cyber traffic systems has been demonstrated* in the wild.
- Potential attack vectors numerous:
  - Broadcasting fake accident reports
  - Compromise of **<u>metering light network.</u>**
- **<u>Resiliency to attack</u>** through fault detection and modeling/sensing discrepancies.



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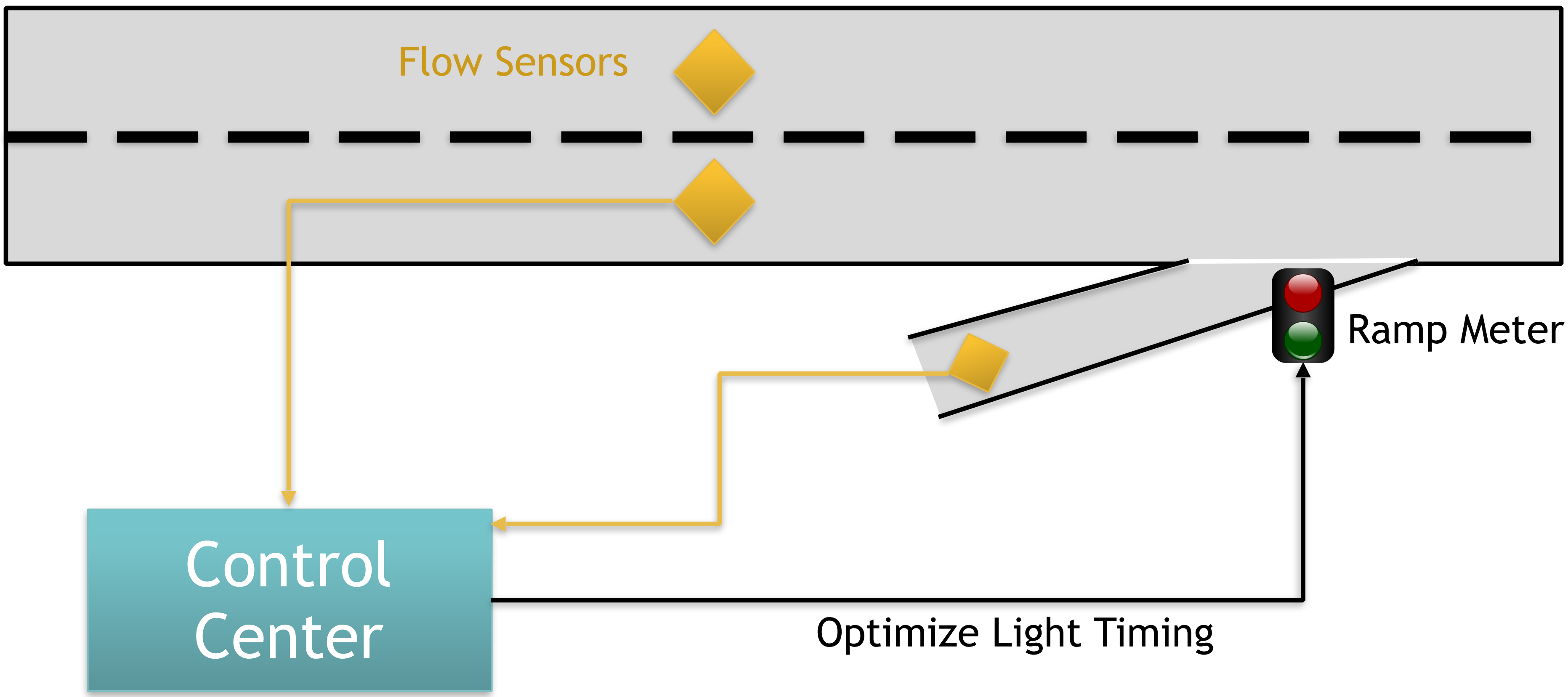
Freeway Traffic systems



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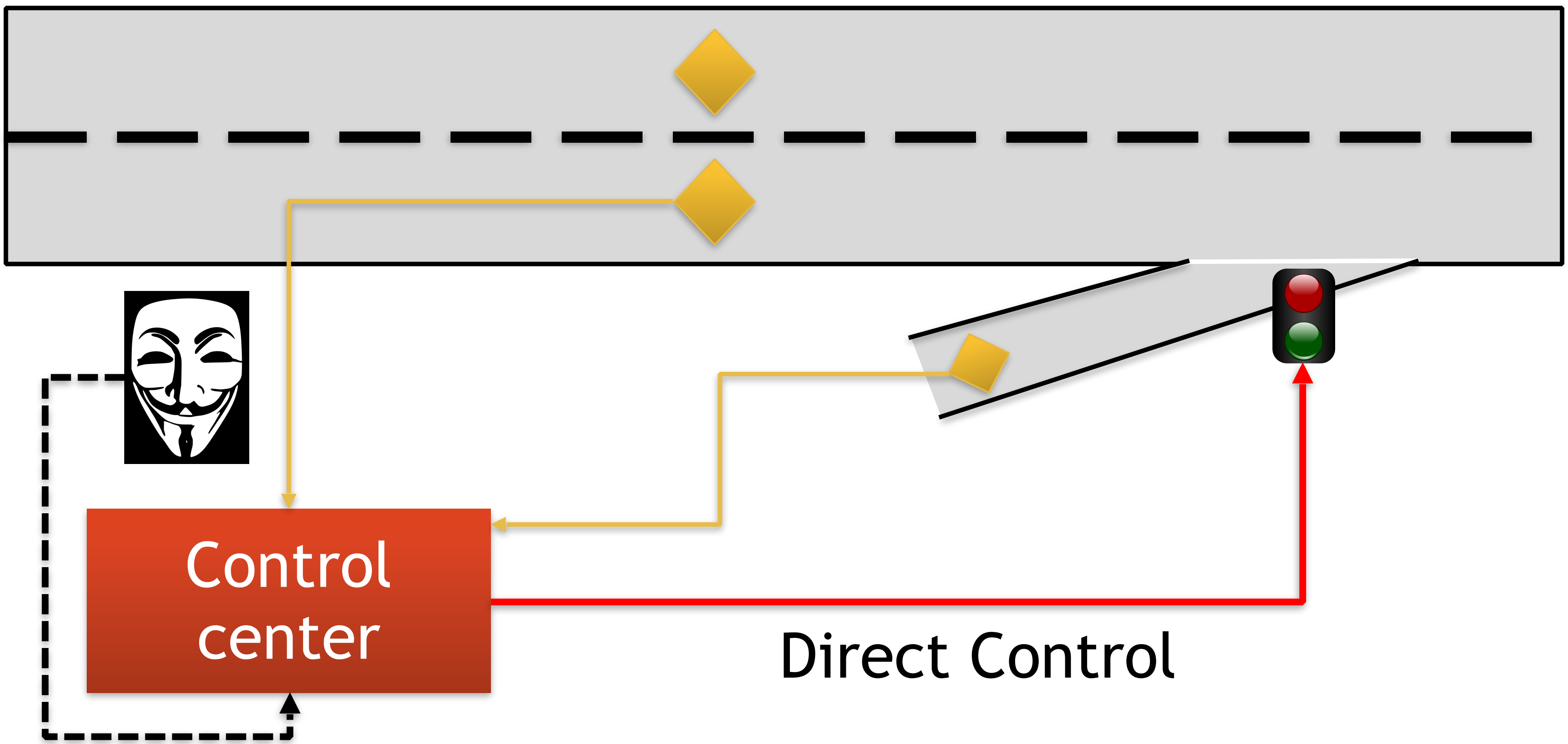
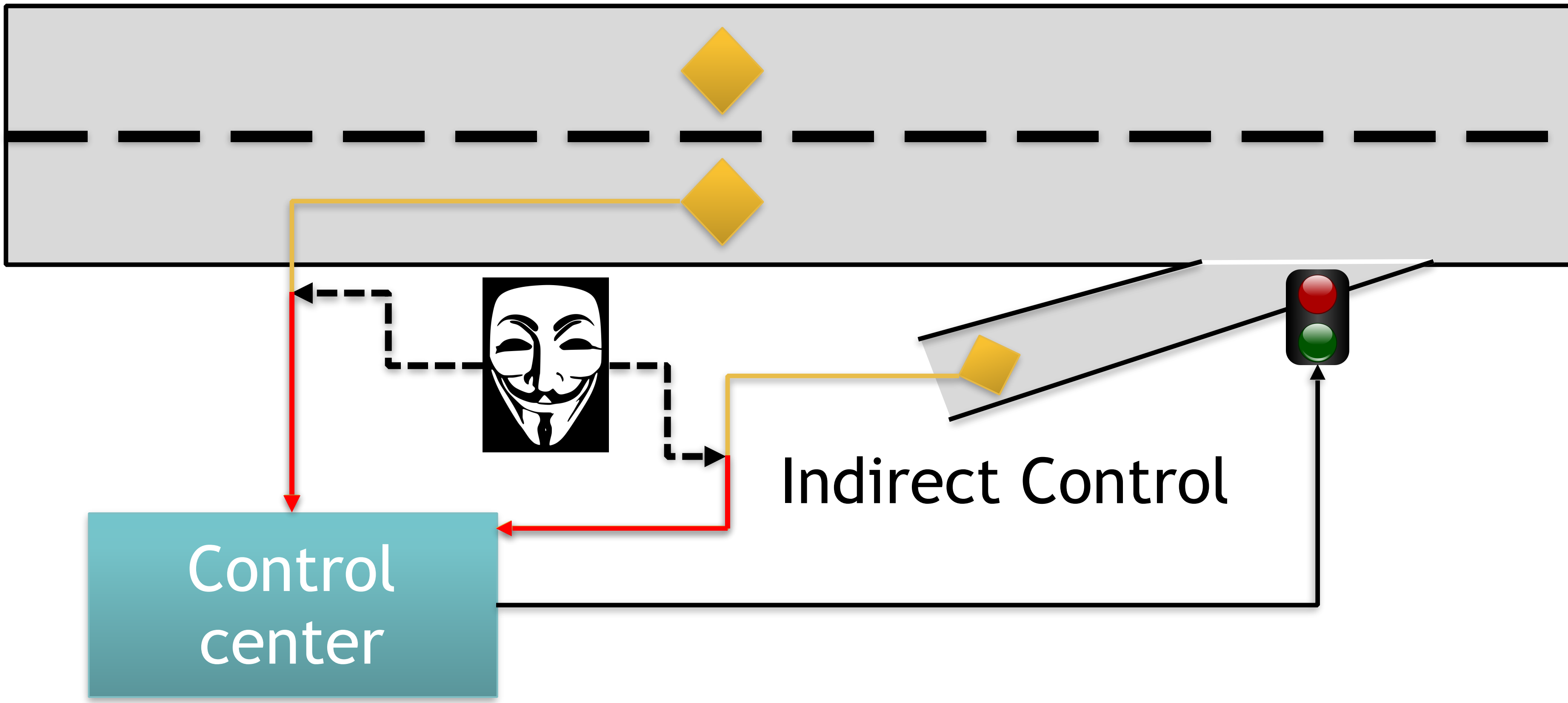
Compromise : complete takeover



Compromise : spoofing the sensors



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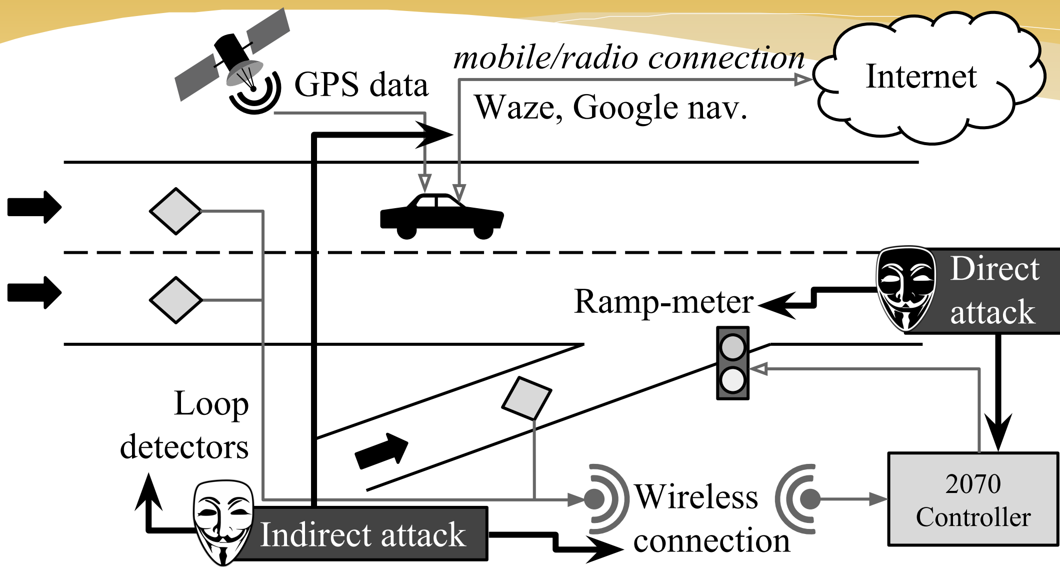
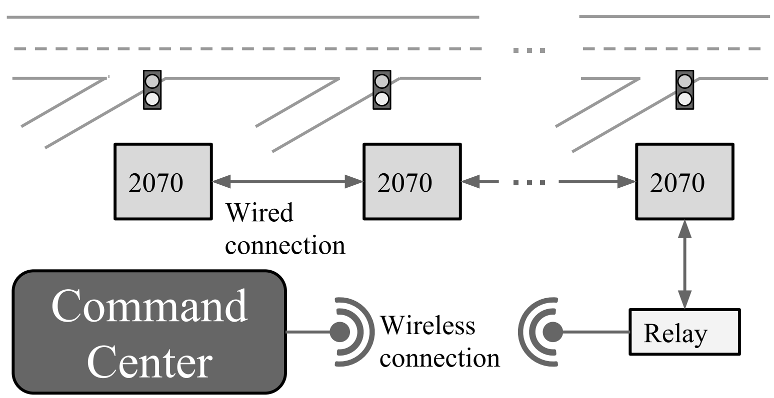
Vulnerability Points



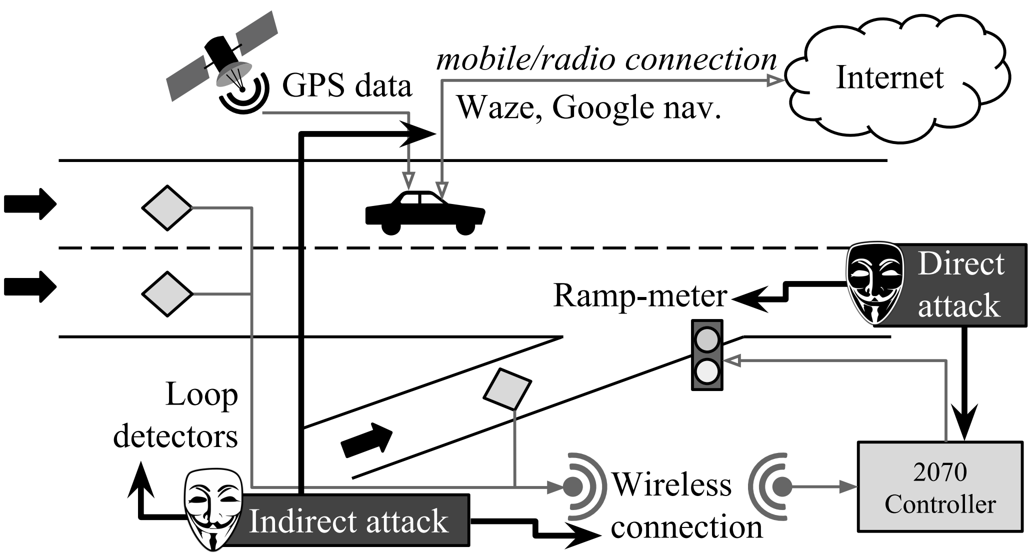
Local Architecture

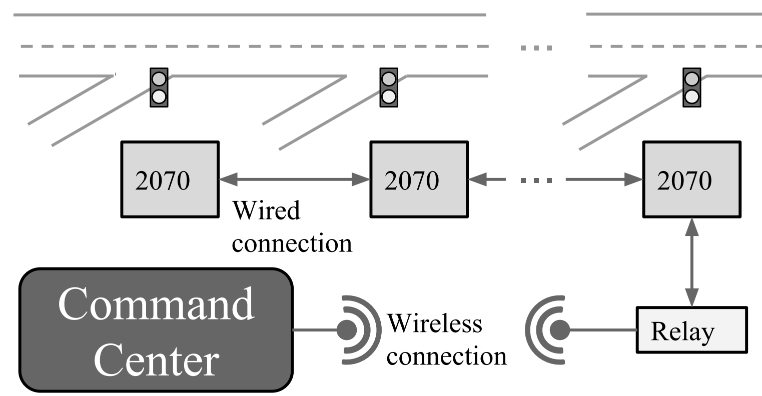


Networked Meters

Vulnerability Points Taxonomy

Attack Description	Access	Control	Complexity	Cost
copper theft/clipping wires	physical	low	low	low
replacing a single sensor/actuator	physical	low	low	low
attacking a single sensor/actuator	locality	low	medium	low
replacing a single control box	physical	medium	medium	medium
replacing a set of sensors/actuator	physical	medium	medium	medium
attacking a set of sensors/actuator	locality	low	medium	low
replacing a corridor of control boxes	physical	high	medium	medium
attacking a corridor of control boxes	network	high	high	medium
attacking the control center	network	high	high	high
spoofing GPS data	network	medium	high	medium
attacking navigation software	network	medium	medium	medium





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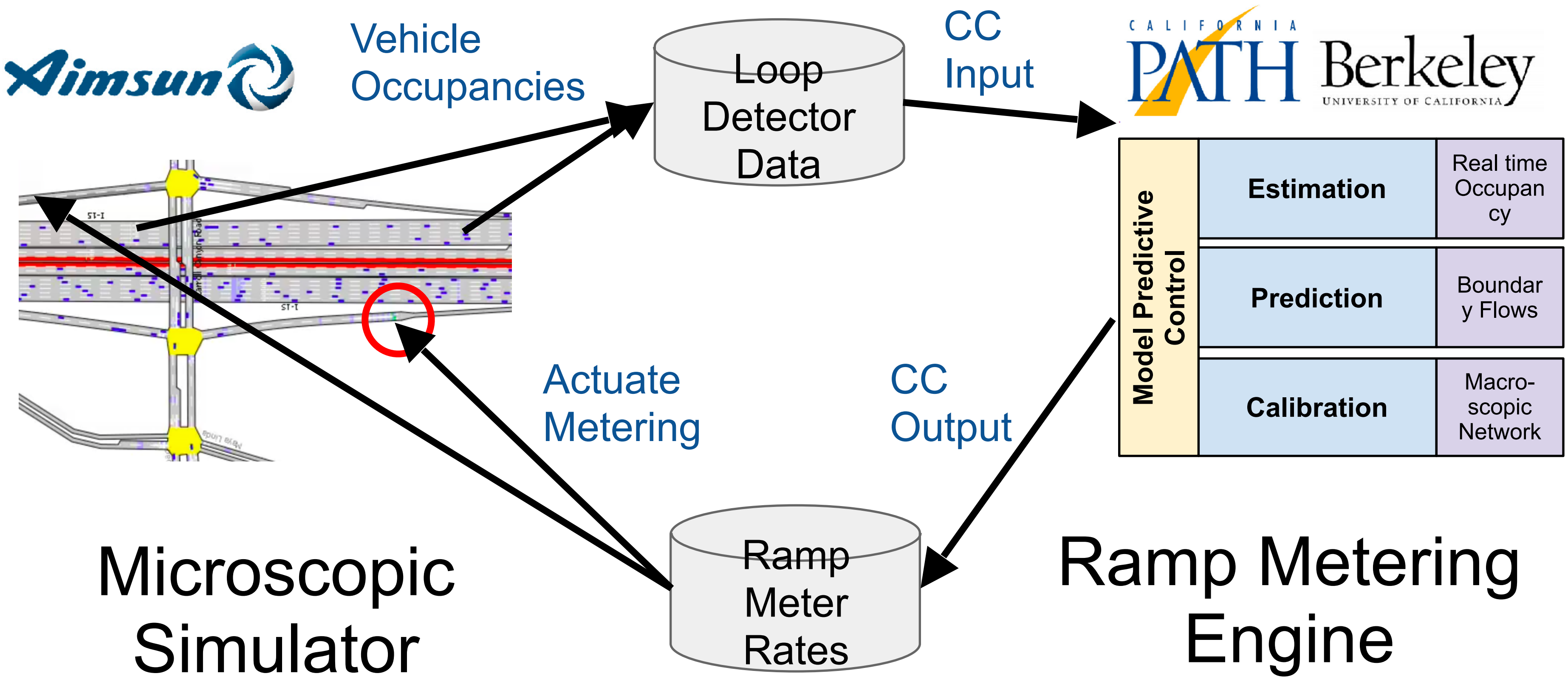
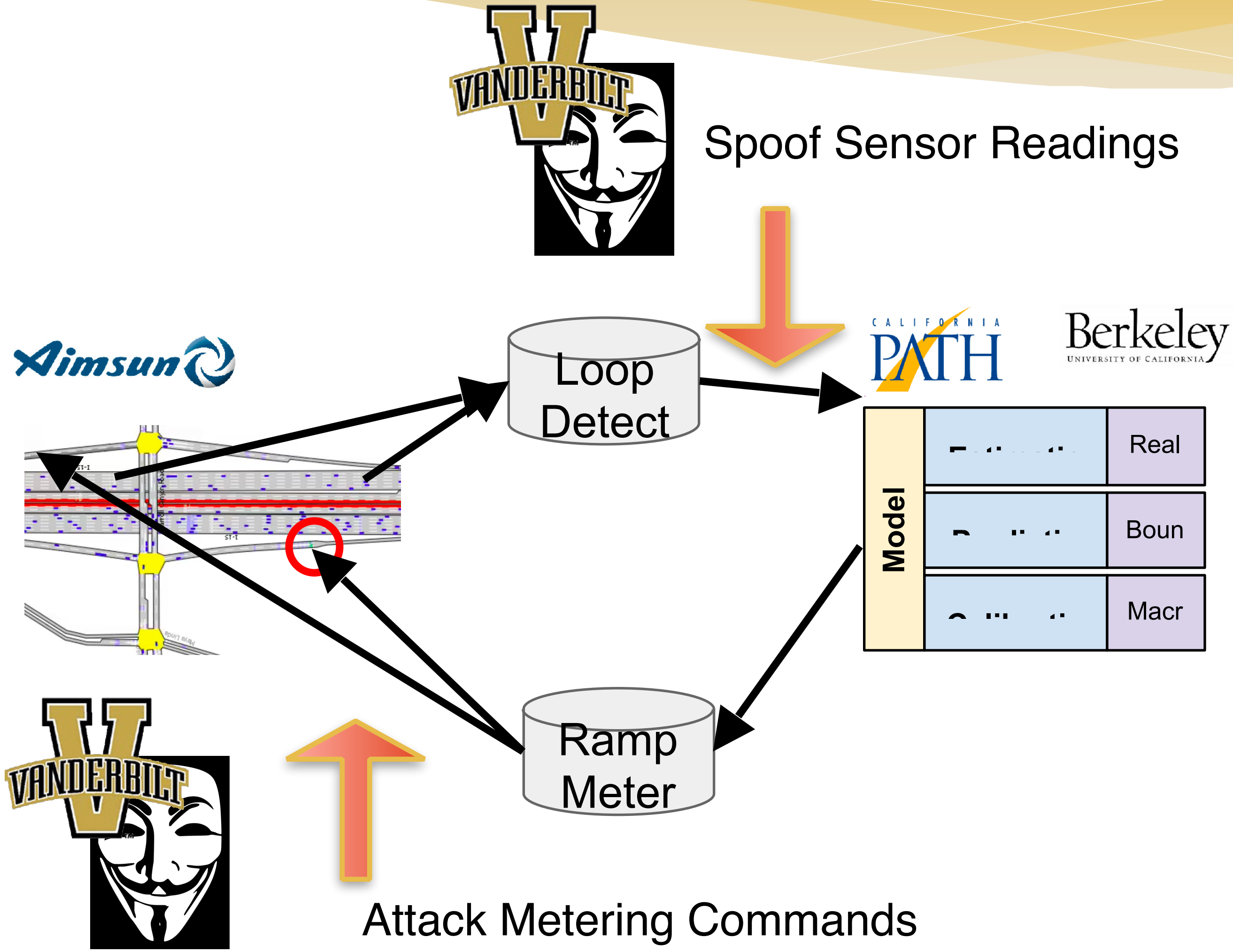
SmartRoads Architecture



SmartRoads Architecture



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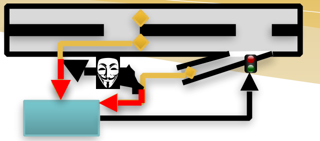
SmartAmerica Scenario



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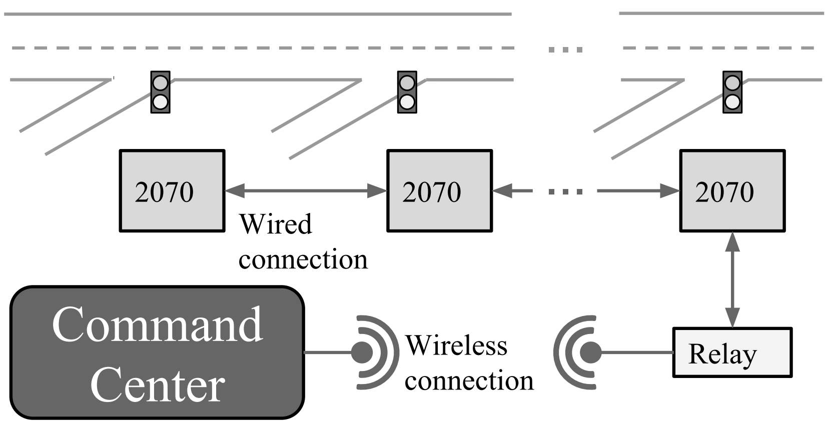
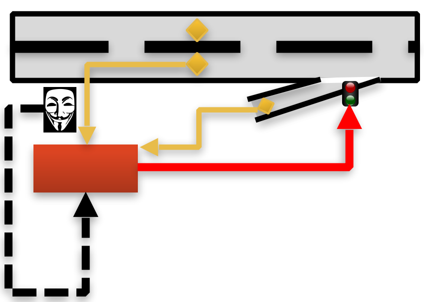
Coordinated Ramp Metering Attacks





MAXIMIZE Attack Objective

Create Jam between Exits 4-6

+

Achieve Free-flow Otherwise
(Stealthy Attack, avoid detection)

+

Limit Onramp Queue Sizes

SUBJECT TO Traffic Dynamics

$$\frac{\partial \rho}{\partial t} + \frac{\partial f(\rho)}{\partial x} = 0$$

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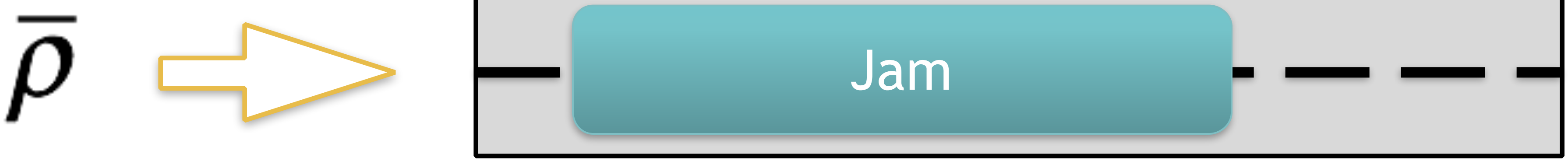
Finite Horizon Optimal Control Formulation

- Discretize continuous PDE dynamics (Godunov's method)

$$H_{i,t} = \rho_{i,t} - \rho_{i,t-1} + \frac{\Delta t}{\Delta x}\left(f^{\text{in}}{}_{i,t-1} - f^{\text{out}}{}_{i,t-1}\right) = 0$$

- **Objective:** State tracking $\min_{u \in U} J = \sum_i \sum_t \| \rho_{i,t} - \bar{\rho}_{i,t} \|$



$$\min_{\mathbf{u} \in U} J\left(\mathbf{u}, \rho\right)$$

$$\text{s.t.} \quad H\left(\mathbf{u}, \rho\right) = 0$$

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Finite-horizon Optimal Control Problem

$$\min_{\mathbf{u}\in U} \underbrace{\sum_{t=1}^{T-1}\sum_{i=1}^{N} f\left(u_{i,t},\rho_{i,t}\right)}_{\text{Running Cost}} + \underbrace{\sum_{i=1}^{N} f_T\left(u_{i,T},\rho_{i,T}\right)}_{\text{Terminal Cost}}$$

subject to system dynamics:

$$\begin{aligned}\rho_{i,0} =& \rho_i^0\\ \rho_{i,t+1} =& \rho_{i,t} + \frac{\triangle t}{\triangle x}\left(G\left(\rho_{i-1,t},\rho_{i-1,t},u_{i,t}\right) - \right.\\ & \left. G\left(\rho_{i,t},\rho_{i+1,t},u_{i,t}\right)\right)\\ & \forall i \in [1,N], \forall t \in [1,T]\end{aligned}$$

$$\min_{\mathbf{u}\in U} J\left(\mathbf{u},\rho\right)$$

$$\text{s.t. } H\left(\mathbf{u},\rho\right) = 0$$

*Non-linear
*Non-smooth
*Non-convex

* Performing gradient descent w/ finite-differences i<u>**nfeasible for large networks!**</u>

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Adjoint Formulation

$$\min_{\mathbf{u}\in U} J(\mathbf{u},\rho)$$
$$\text{s.t.}\quad H(\mathbf{u},\rho)=0$$

Compute gradient: $\nabla_{\mathbf{u}} J = \frac{\partial J}{\partial \mathbf{u}} + \frac{\partial J}{\partial \rho}\frac{d\rho}{d\mathbf{u}}$

Easy

Hard

Eliminate $\frac{d\rho}{d\mathbf{u}}$ using system dynamics: $\nabla_{\mathbf{u}} H = \frac{\partial H}{\partial \mathbf{u}} + \frac{\partial H}{\partial \rho}\frac{d\rho}{d\mathbf{u}} = 0$

$$\nabla_{\mathbf{u}} J =$$
$$J_u + J_\rho \rho_u + \lambda^T\left[H_\rho + H_u\right] =$$
$$\left(J_\rho + \lambda^T H_\rho\right)\rho_u + \left(J_u + \lambda^T H_u\right)$$

⟺

$$\nabla_{\mathbf{u}} J =$$
$$J_u + \lambda^T H_u$$
$$\text{s.t.}\quad H_\rho^T \lambda = -H_u^T$$

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Coordinated Freeway Control using **Adjoint** Methods

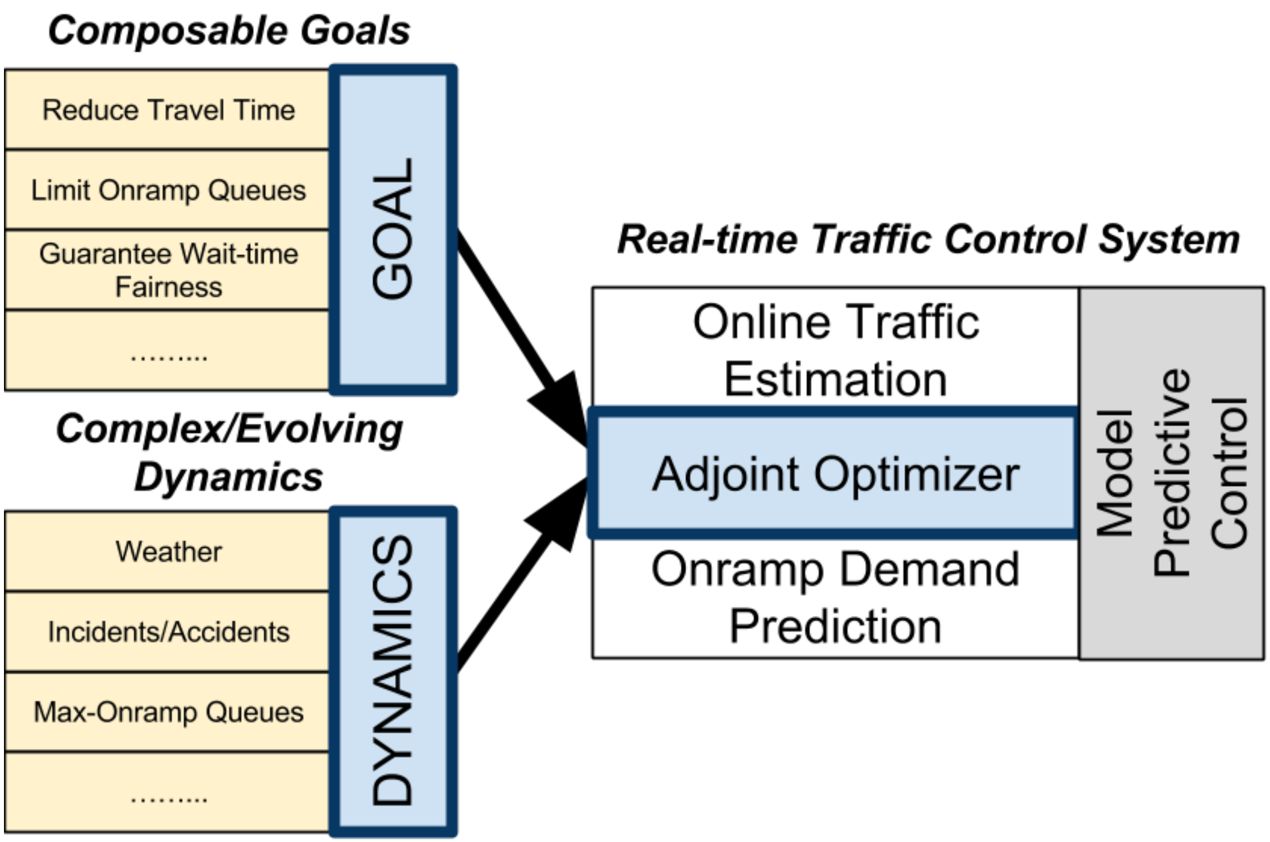
Composable Goals

	GOAL
Reduce Travel Time	
Limit Onramp Queues	
Guarantee Wait-time Fairness	
………	

Complex/Evolving Dynamics

	DYNAMICS
Weather	
Incidents/Accidents	
Max-Onramp Queues	
………	

Coordinated Freeway Control using **Adjoint** Methods



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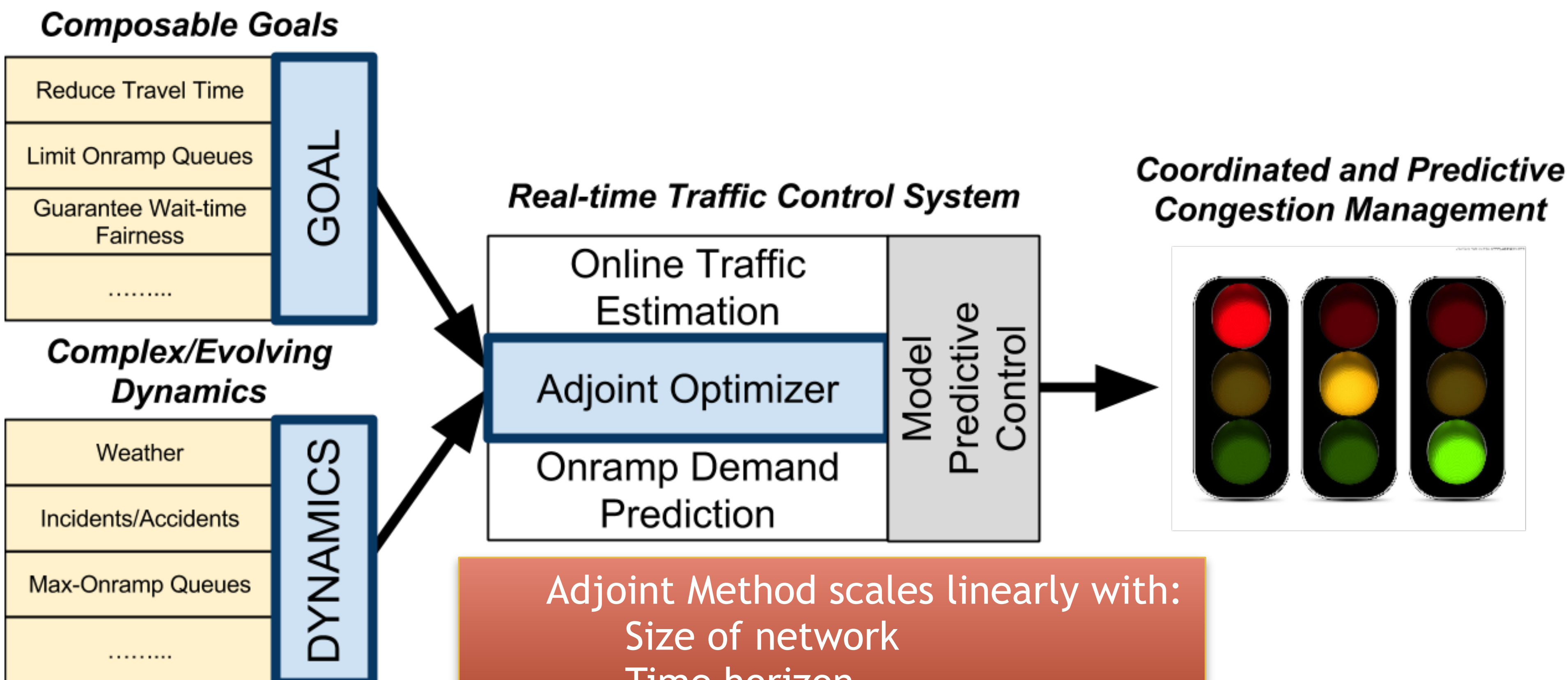
Coordinated Freeway Control using **Adjoint** Methods



Adjoint Method scales linearly with:
- Size of network
- Time horizon

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Gradient Descent

* Compute gradient of constrained problem via ***adjoint***

$$\min_{\mathbf{u}\in U} J(\mathbf{u},\rho)$$
$$\text{s.t. } H(\mathbf{u},\rho)=0$$

$$\nabla_{\mathbf{u}} J = J_u + \lambda^T H_u$$
$$\text{s.t. } H_\rho^T \lambda = -H_u^T$$

* Embed within gradient descent loop:
  * 1) Compute new state $\rho^k : H(\rho^k, u^k) = 0$ *[forward sim]*
  * 2) Compute gradient $\nabla_u J(\rho^k, u^k)$
  * 3) Update $u^{k+1} = f(u^1, \ldots, u^k, \nabla_u J^k)$ *[e.g. L-BFGS]*
  * 4) Loop $k \leftarrow k+1$

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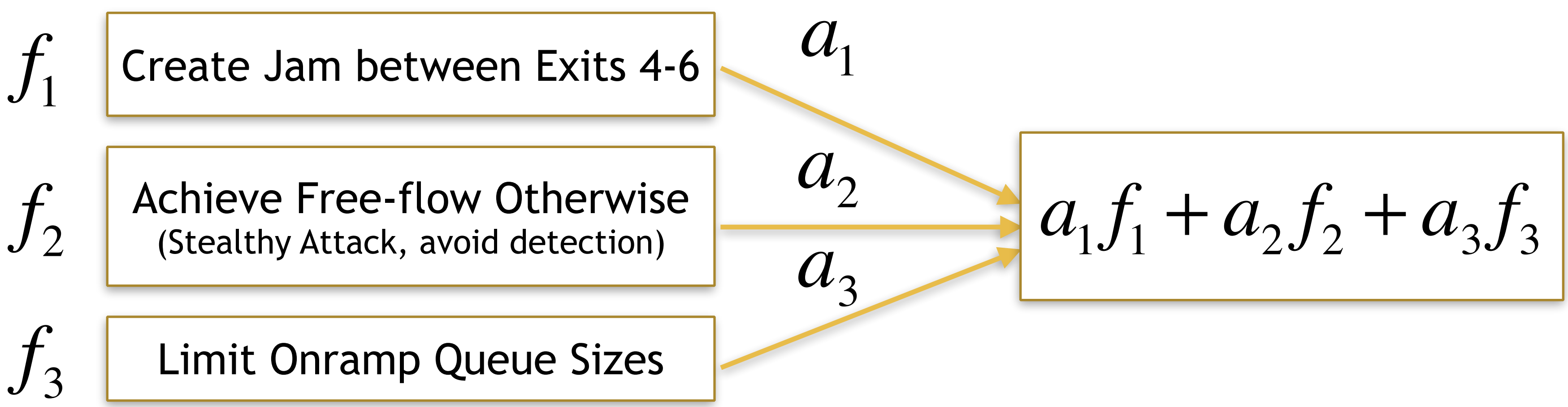
Multi-objective Optimization for Attacks

- **Goal:** Achieve success on many conflicting goals simultaneously
- **Solution:** Scalarization
  - Objective -> linear combination of sub-objectives.



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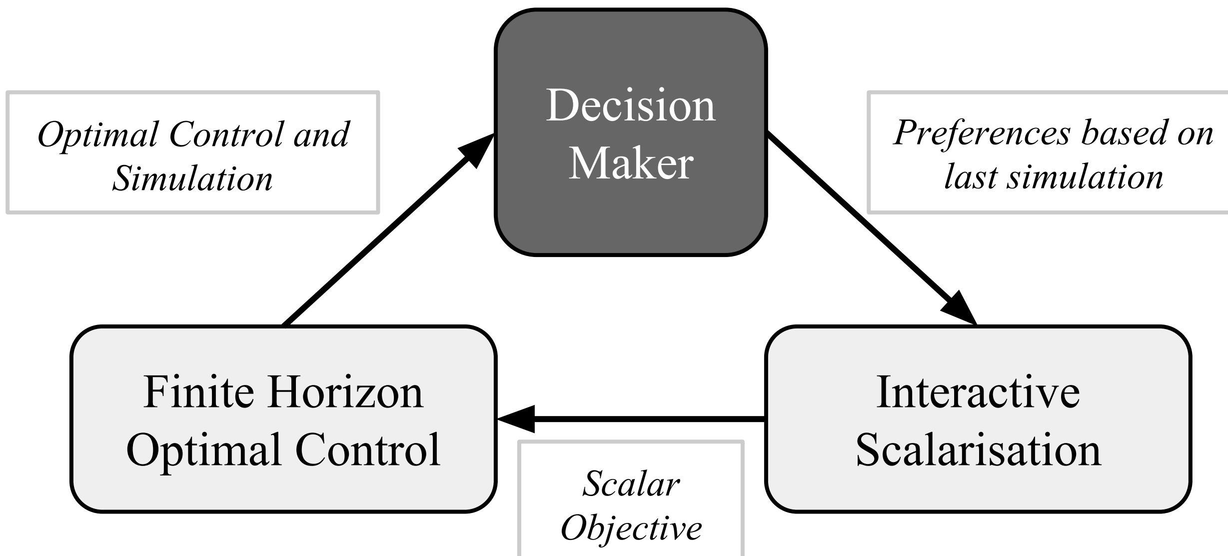
Interactive Optimization

* Use human expertise to find proper a_i coefficients **during** exploration



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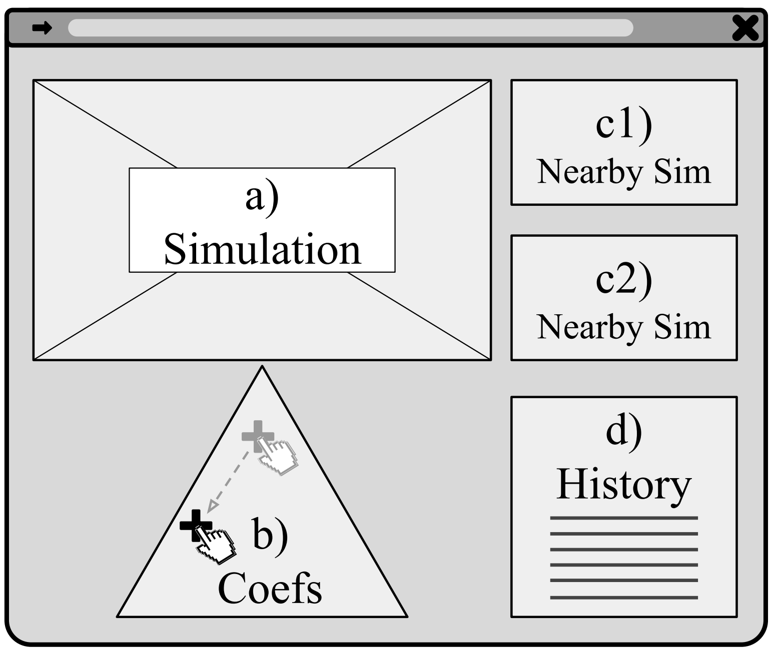
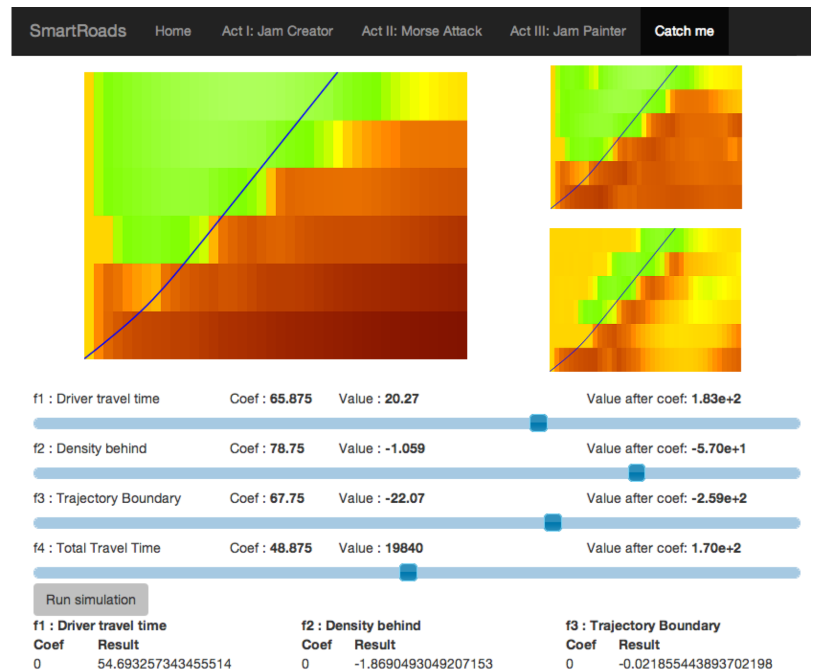
Interactive Optimization

* Use human expertise to find proper a_i coefficients





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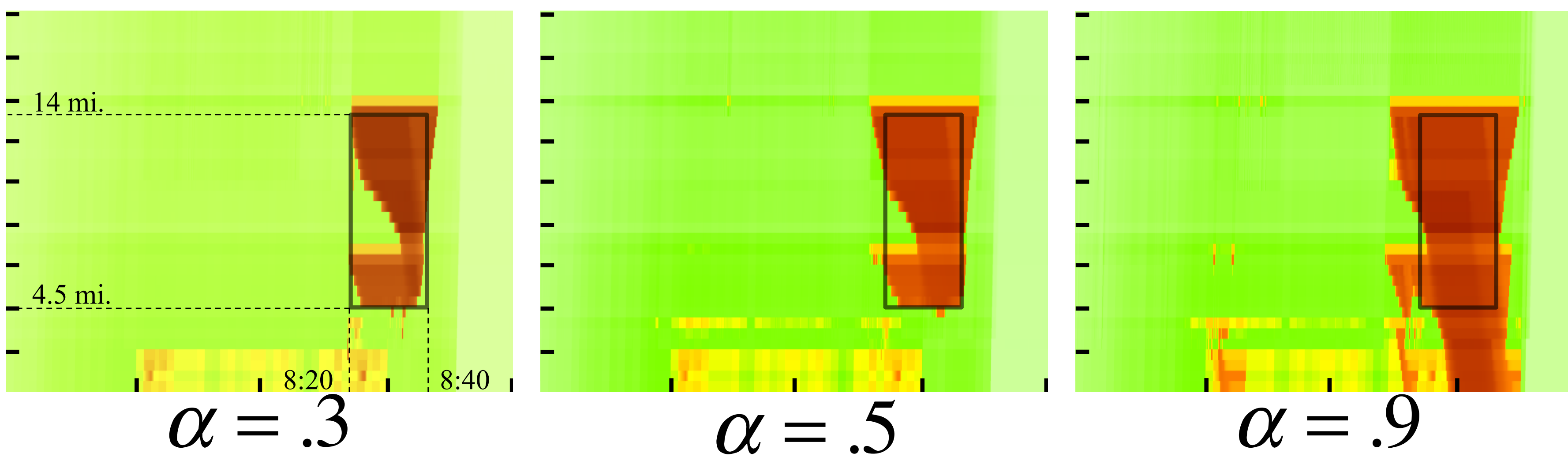
Box Attack Sim: I15 Freeway in San Diego

- Create isolated, precise jam over predetermined time.
- **Balance** between maximizing jam in "box" and minimizing free-flow outside box.

$$f = \alpha f_{\text{jam box}} + (1-\alpha) f_{\text{clear outside box}}$$



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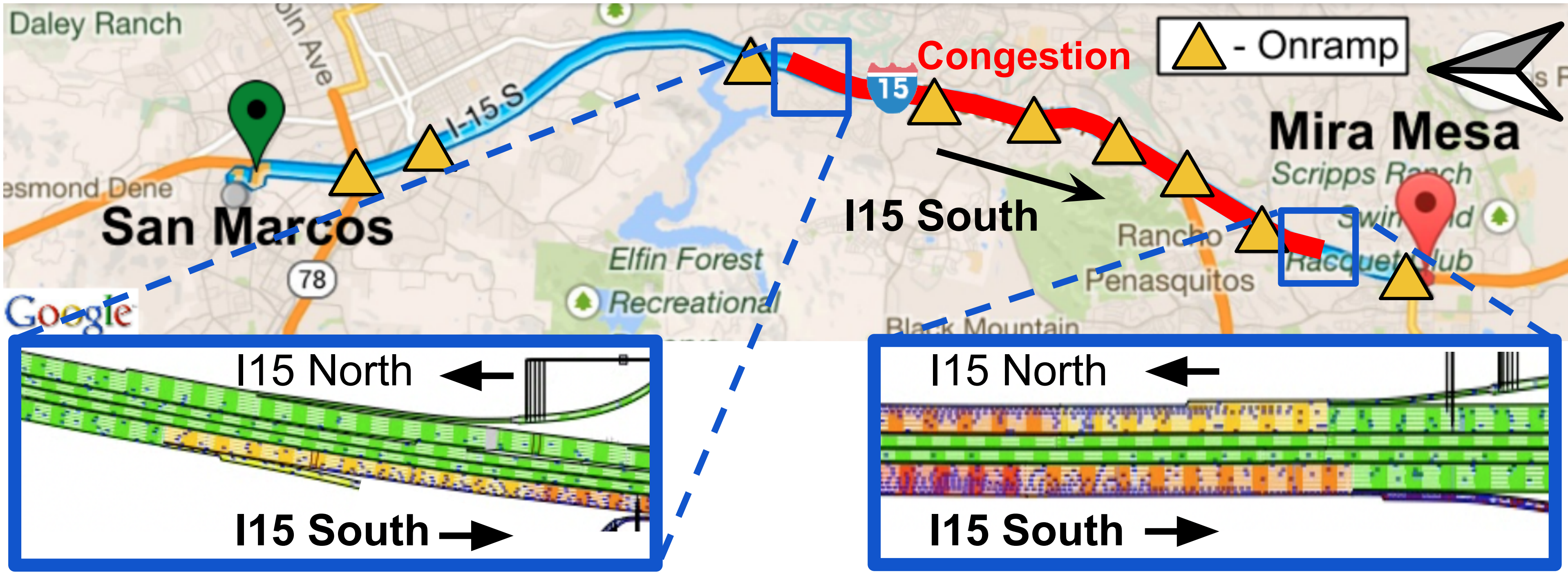
Box Attack Sim: I15 Freeway in San Diego



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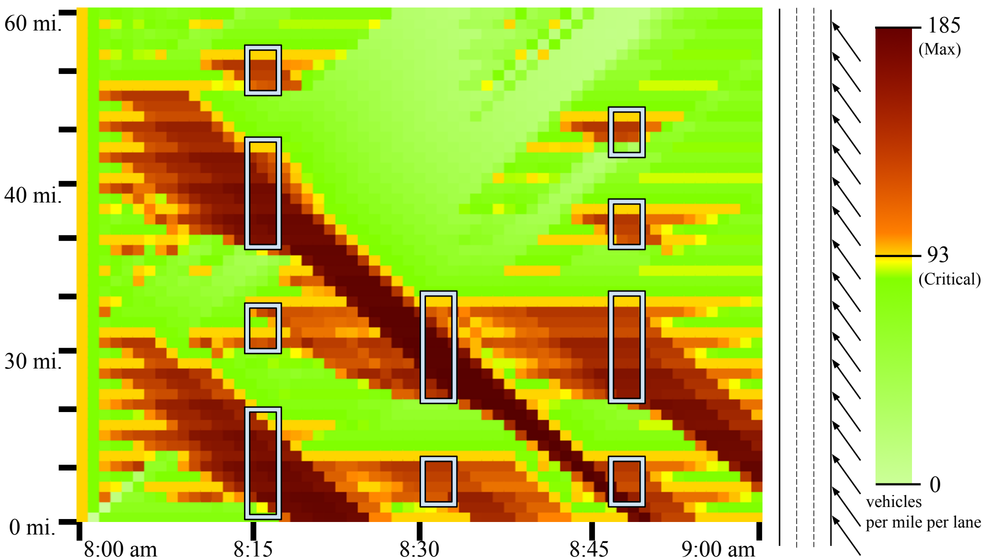
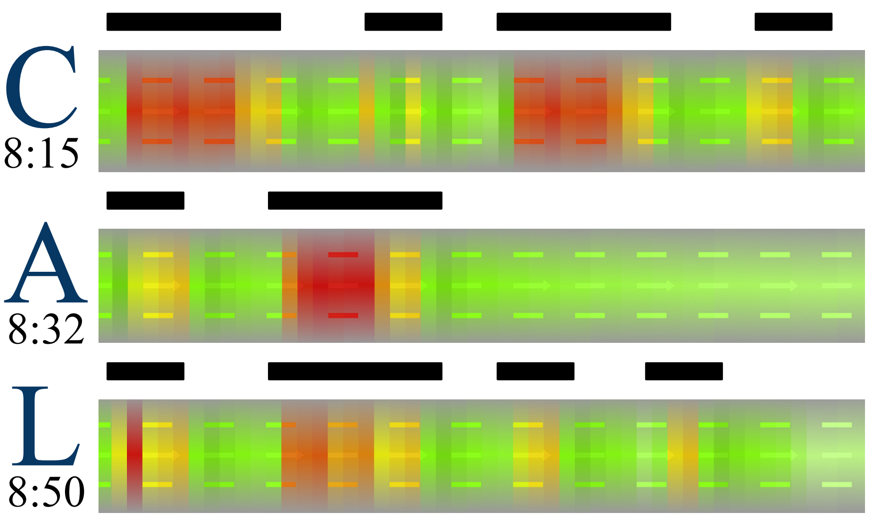
Box Attack Sim: I15 Freeway in San Diego

Morse Code Attack on the Freeway

- Use Box Objective is “building block” for more sophisticated attacks
- Example: Write Morse code on freeway with traffic jams



Space-time Diagram



Time Slices along Freeway

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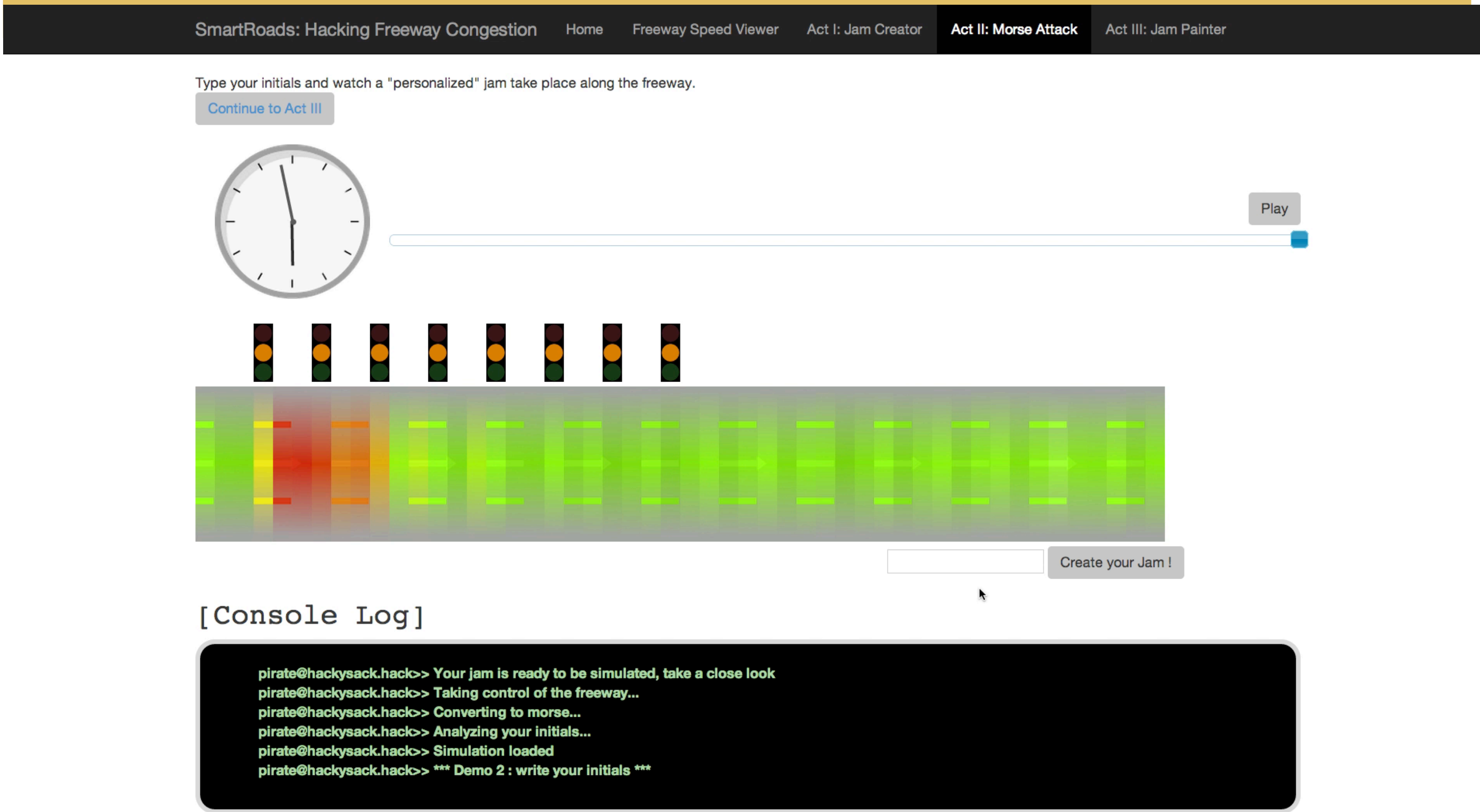
Morse Code Attack on the Freeway



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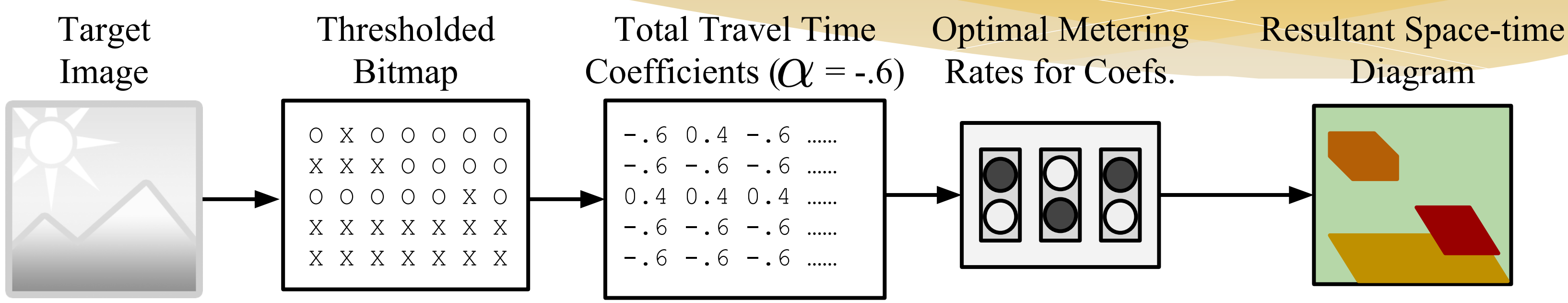
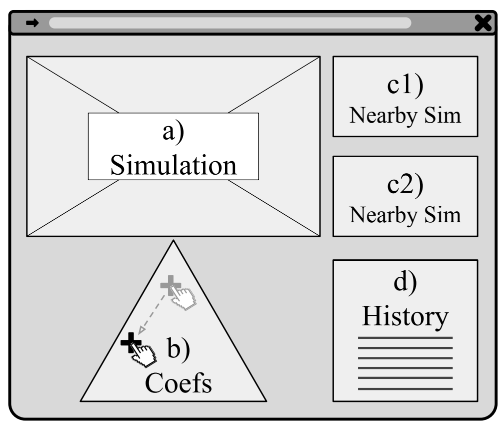
Drawing Cal On the Freeway



Attack Example: *CATCH ME IF YOU CAN*

* Attacker wishes to escape vehicles chasing him.
* Three objectives:
  * f_1 Maximize congestion behind driver
  * f_2 Maximize speed change **directly** behind driver trajectory
  * f_3 Minimize travel time otherwise (avoid suspicion)



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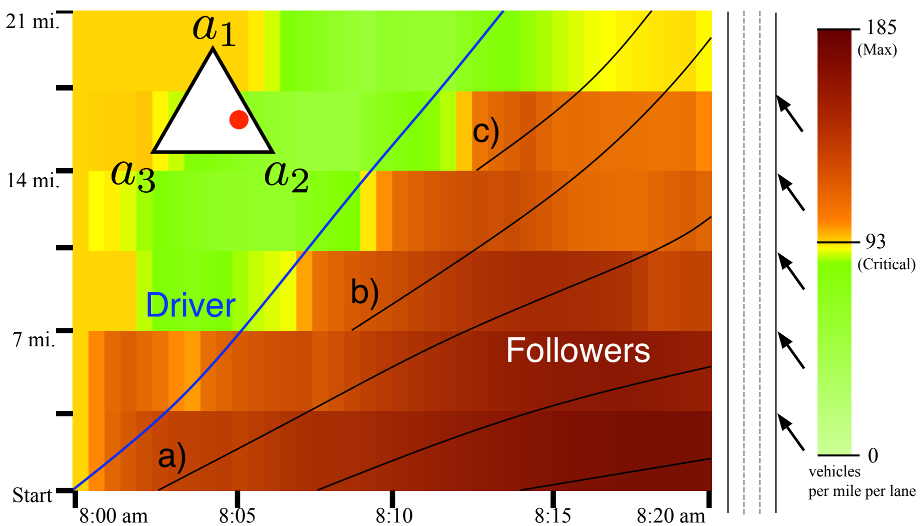
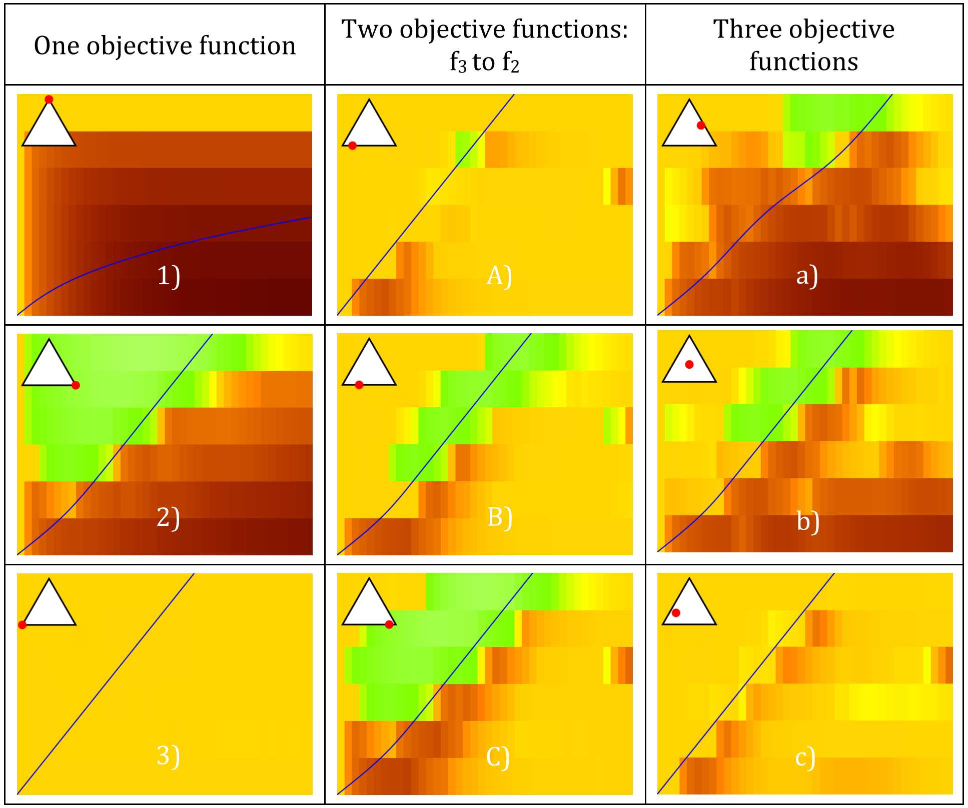
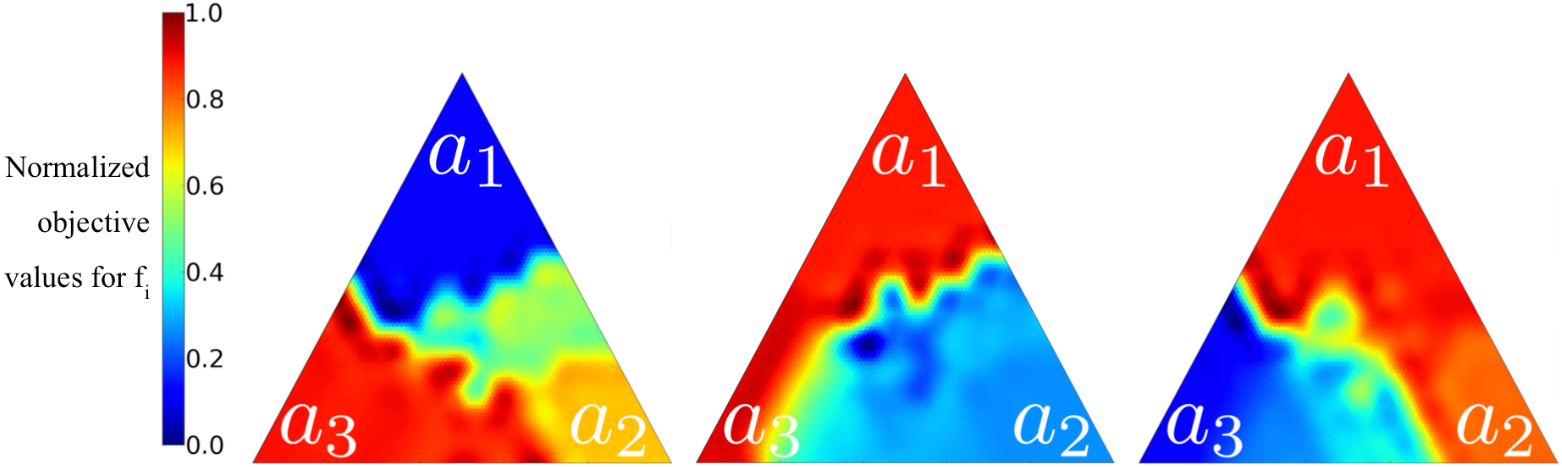
Attack Example: *CATCH ME IF YOU CAN*





A posteriori Optimization

- Explore a_i space, creating a "representative" subset of Pareto solutions



(b) Scaled values of f_1 (c) Scaled values of f_2 (d) Scaled values of f_3

Open Questions

* Risk To Reward Ratio
  * How costly to society are the attacks?
  * How costly is the <u>implementation</u> of the attacks?
* Connected Vehicles/Infrastructure Security
  * What vulnerabilities exist when vehicles are in the loop?
* **Prevention**
  * How can we leverage knowledge traffic dynamics to prevent attacks?

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Publications

- Reilly, J., Martin, S., Payer, M., & Bayen, A. M. (2014). On Cybersecurity of Freeway Control Systems: Analysis of Coordinated Ramp Metering Attacks. Transportation Research Part B Methodological, (In Review)
- Reilly, J., Krichene, W., Delle Monache, M. L., Samaranayake, S., Goatin, P., & Bayen, A. M. (2014). Adjoint-based optimization on a network of discretized scalar conservation law PDEs with applications to coordinated ramp metering. Journal of Optimization Theory and Applications (under Review).
- Reilly, J., & Bayen, A. M. (2014). Distributed Optimization for Shared State Systems: Applications to Decentralized Freeway Control via Subnetwork Splitting. Journal of Computational Physics (In Preparation).
- Delle Monache, M. L., Reilly, J., Samaranayake, S., Krichene, W., Goatin, P., & Bayen, A. M. (2014). A PDE-ODE model for a junction with ramp buffer. SIAM Journal on Applied Mathematics, 74(1), 22–39.

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Thank you for listening!

Questions?