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FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Traffic Jams on Demand:
Precision Attacks on Freeways using Optimal Control Techniques.

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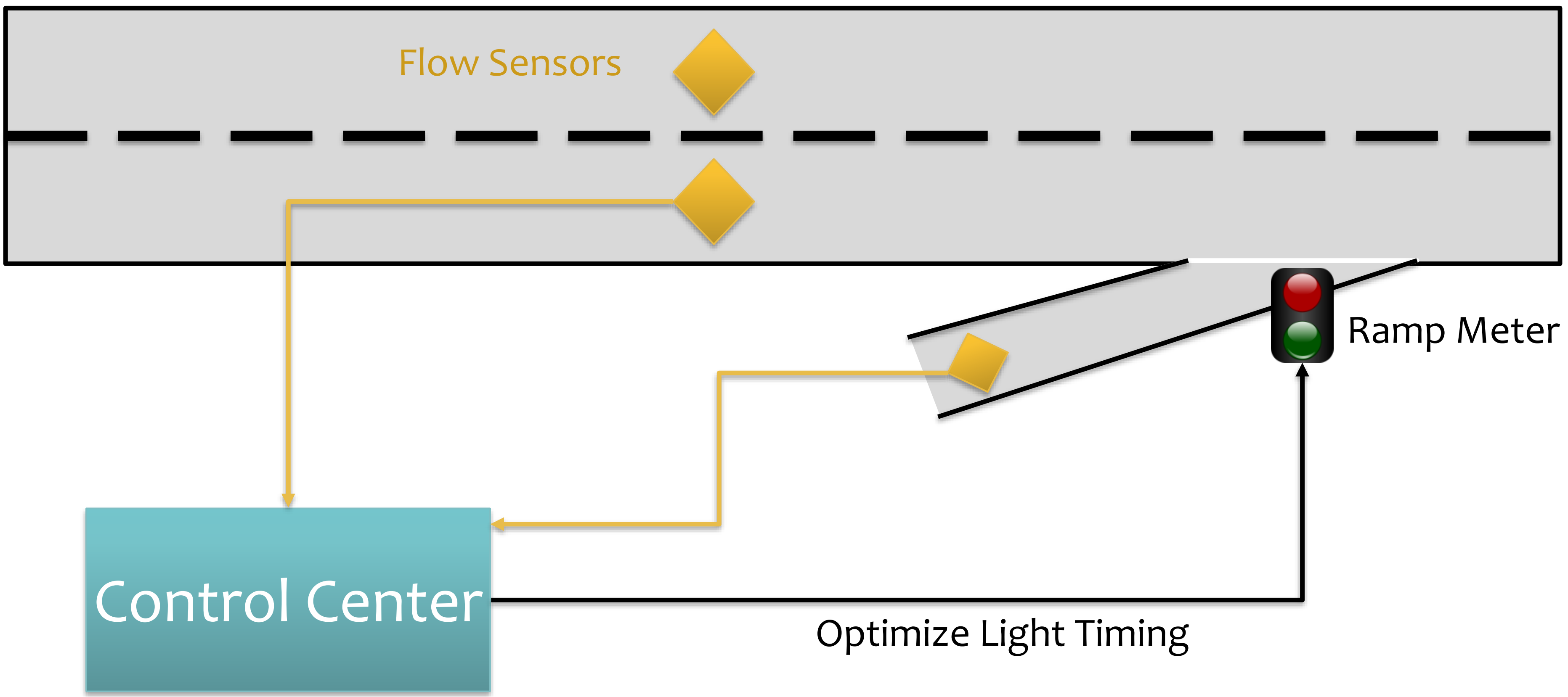
Freeway Traffic systems



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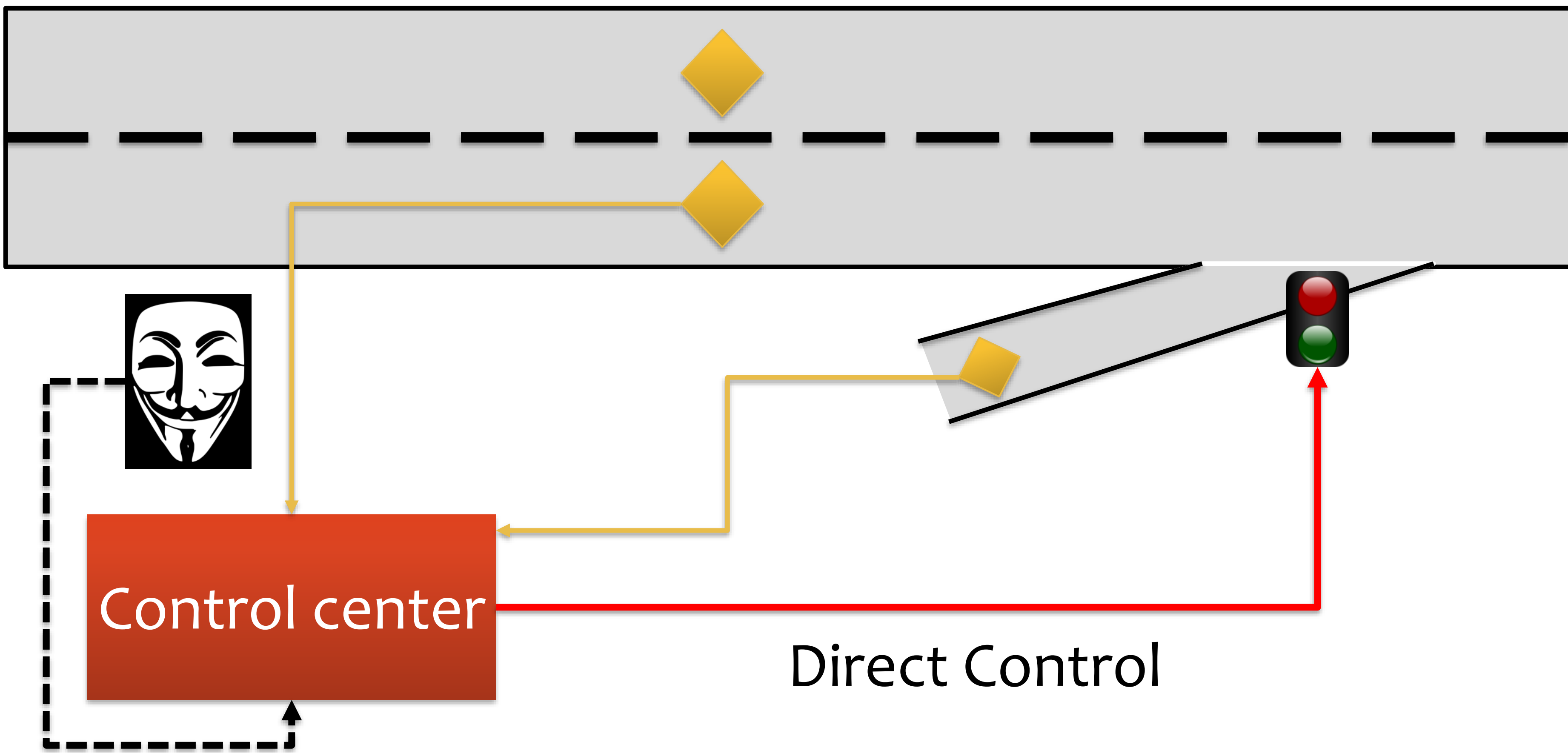
Compromise : complete takeover



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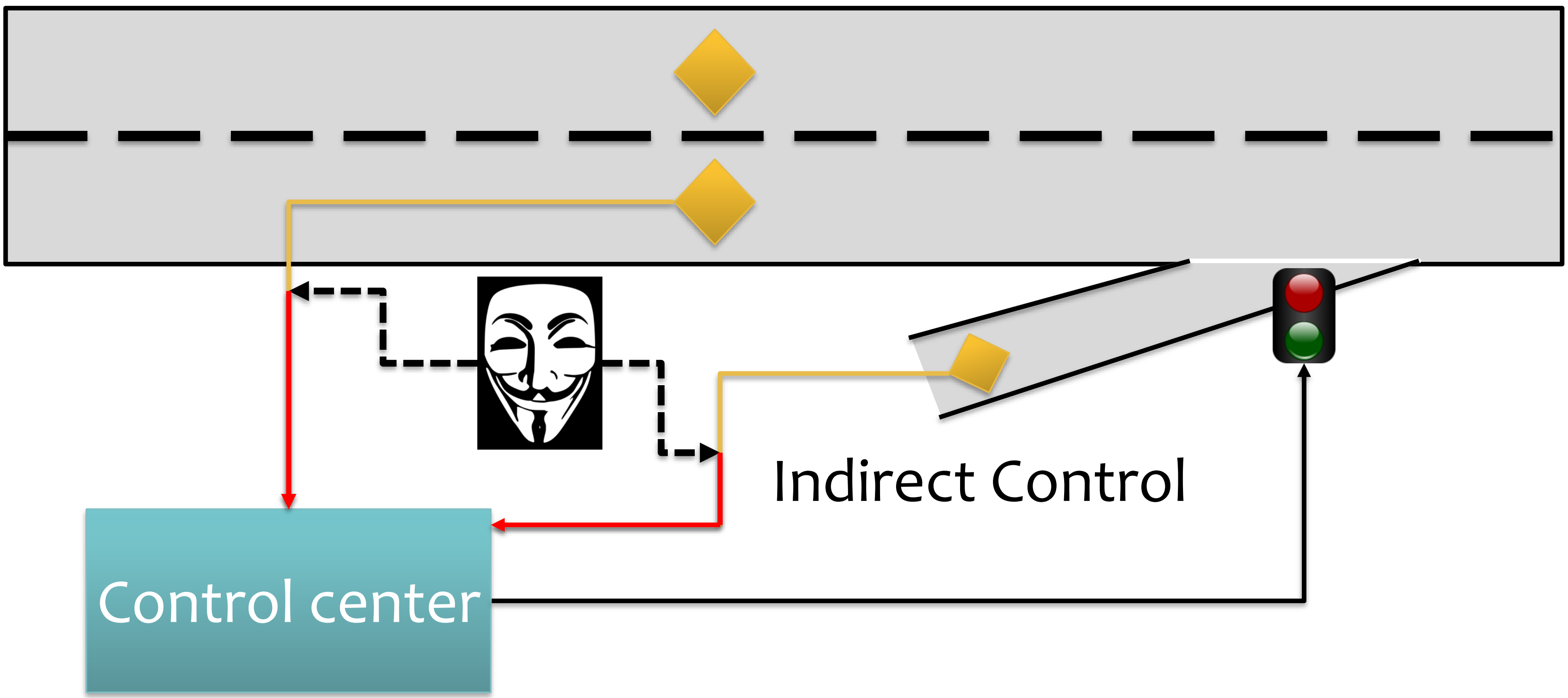
Compromise : spoofing the sensors



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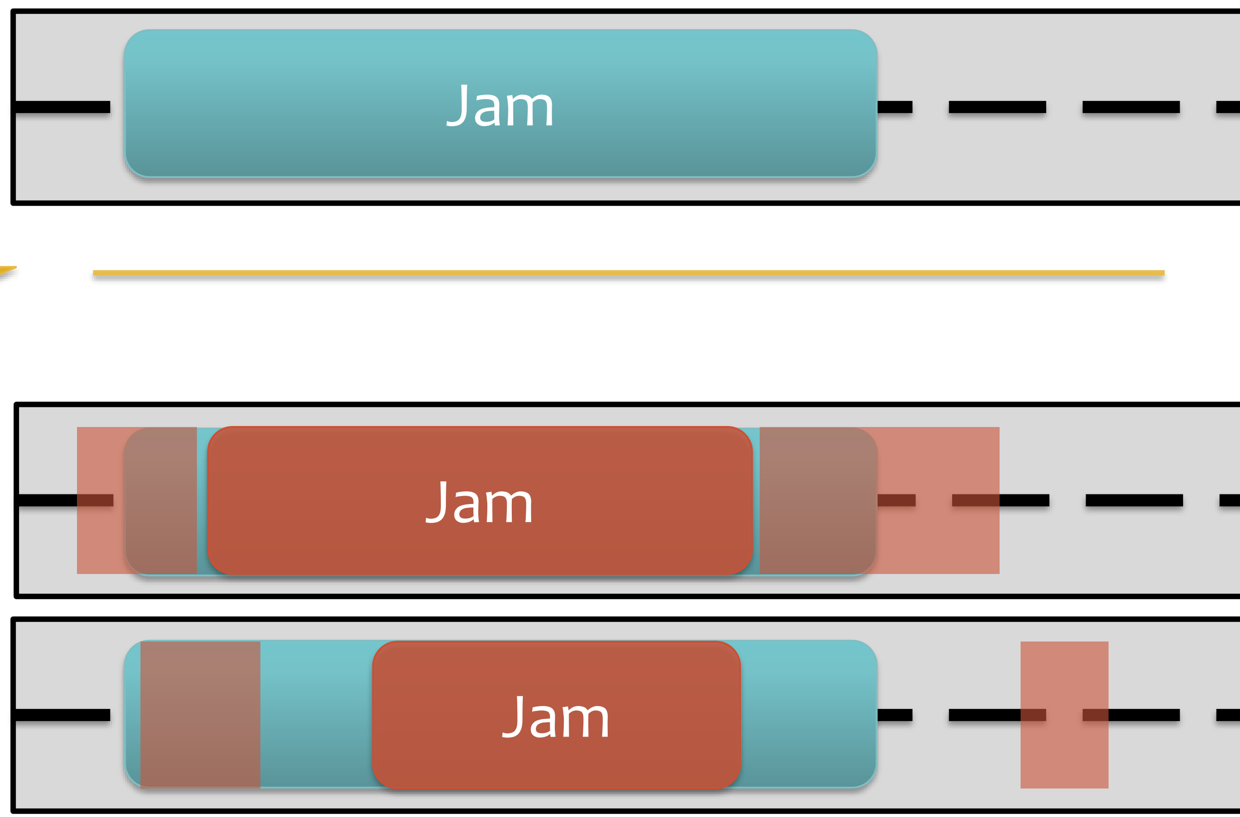
Compromise : spoofing the sensors

Closest Reachable states

Attacker’s optimal objective



- Direct Control
- Sensor Spoofing Only

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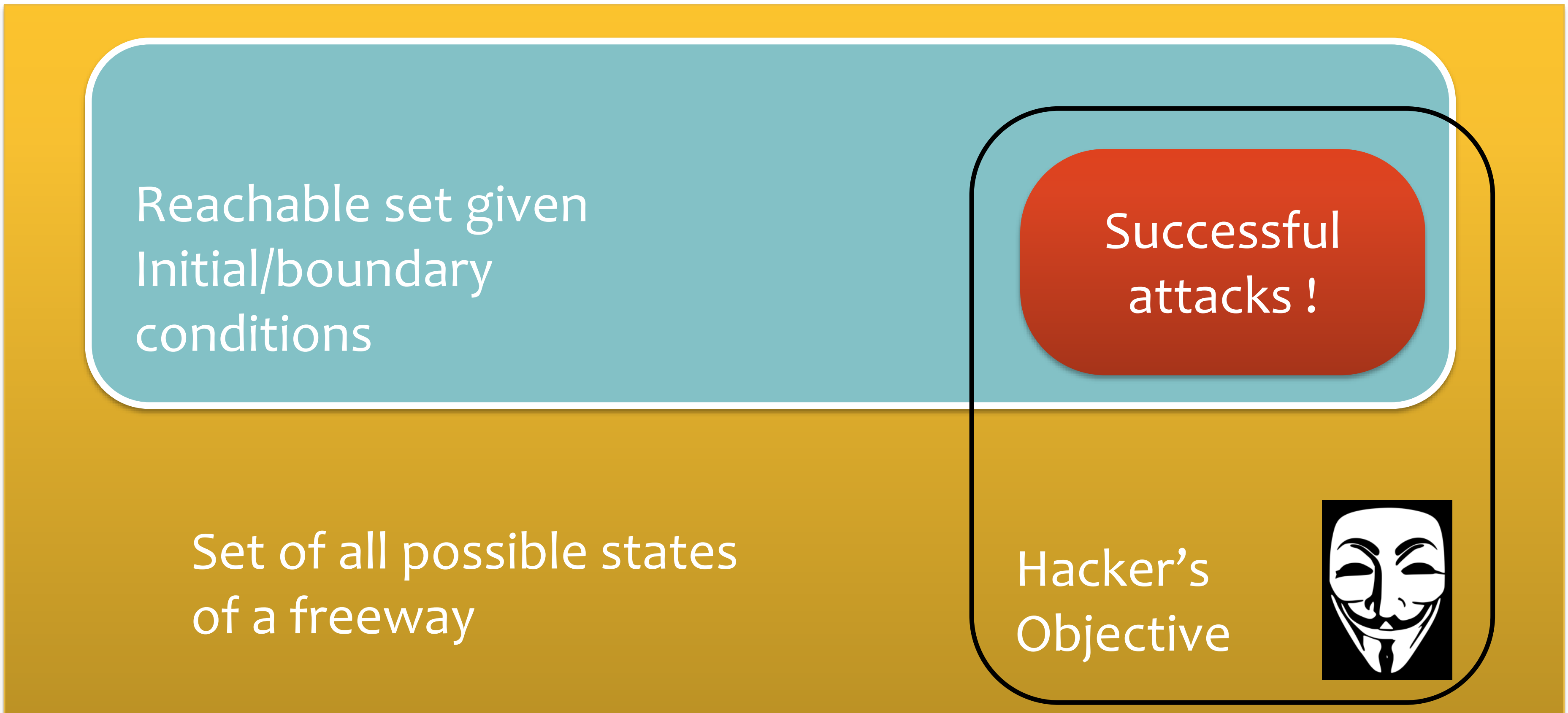
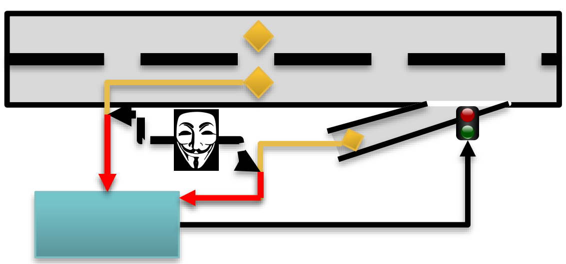
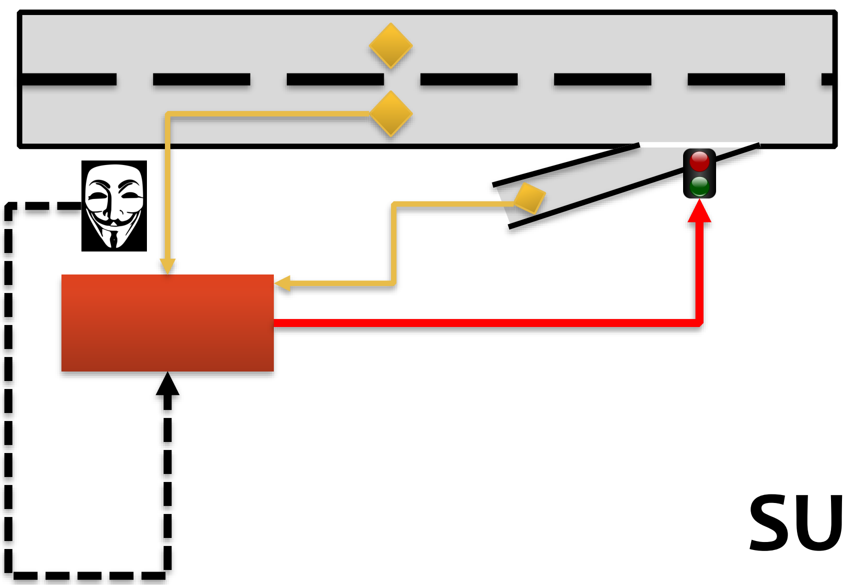
Reachable sets



Sensor Spoofing Attack: Micro-Simulation



Direct Attack: Optimal Control Method



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

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

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

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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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Take-Over-The-Freeway Attack Demo!

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