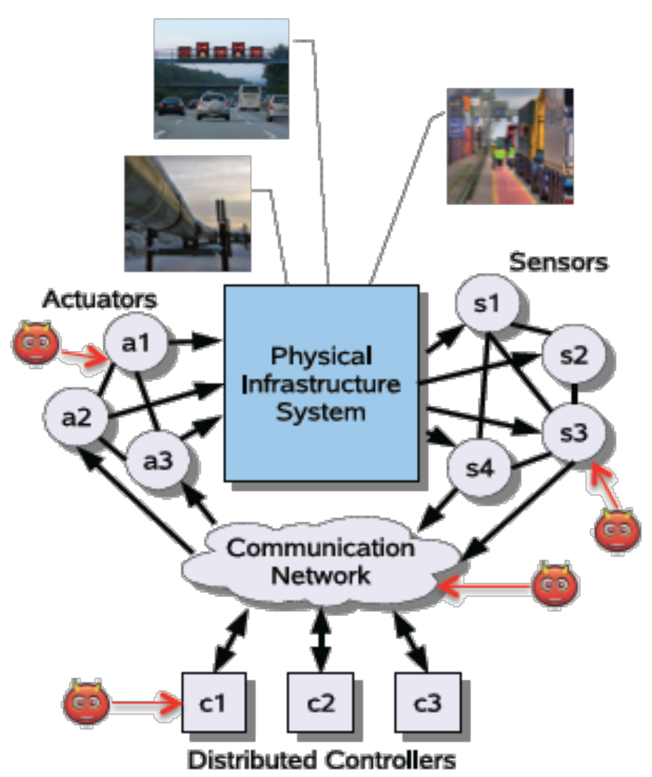
Foundations Of Resilient CybEr-physical Systems (FORCES)

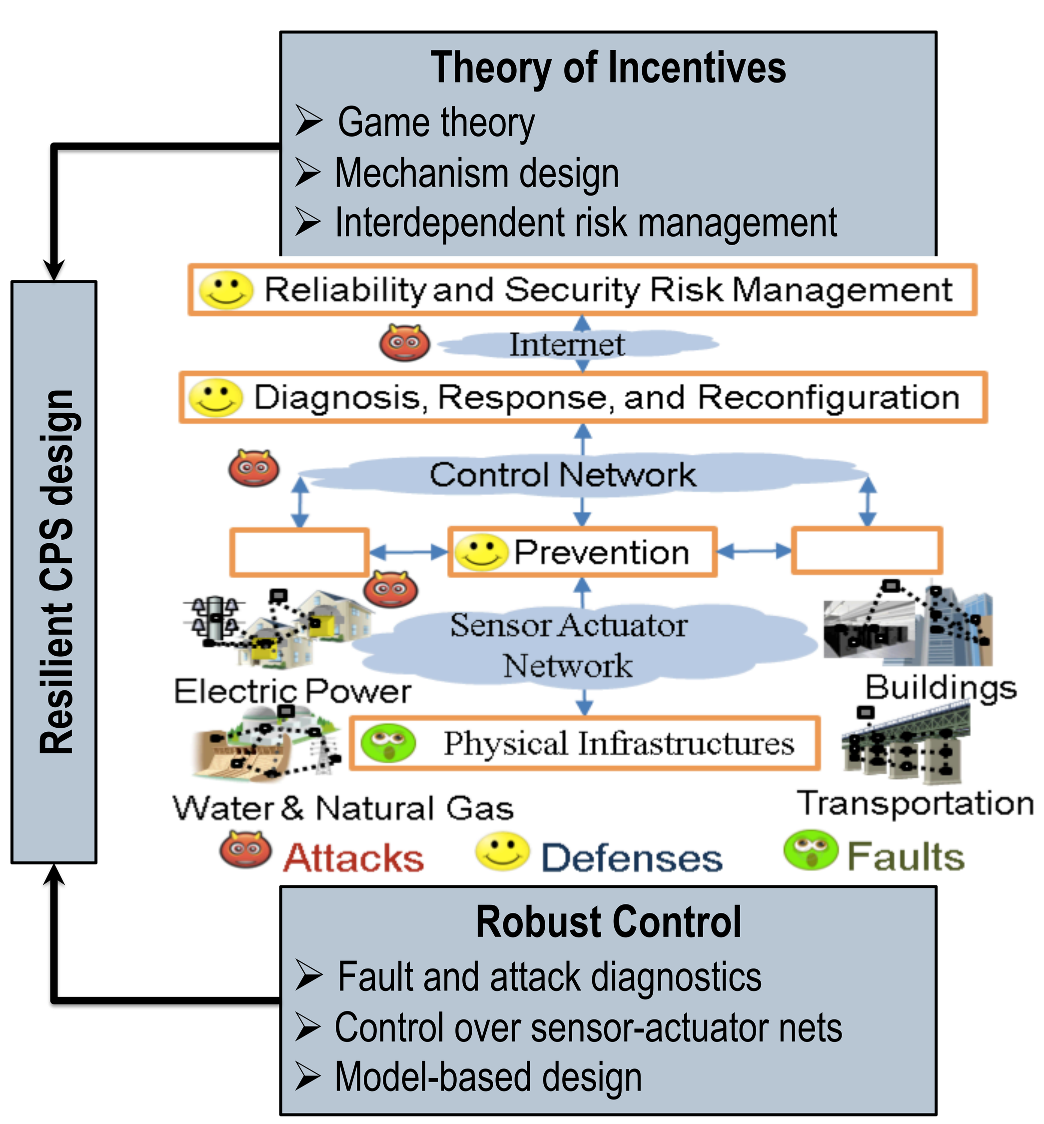
FORCES: Motivation and Approach



- Attributes of Resilience
  - Functional correctness (by design)
  - Robustness to *reliability* failures (faults)
  - Survivability against *security* failures (attacks)
- Challenges to Resilience
  - Spatio-temporal dynamics
  - Many strategic interactions with network interdependencies
  - Inherent uncertainties (public & private)
  - Tightly coupled control and economic incentives

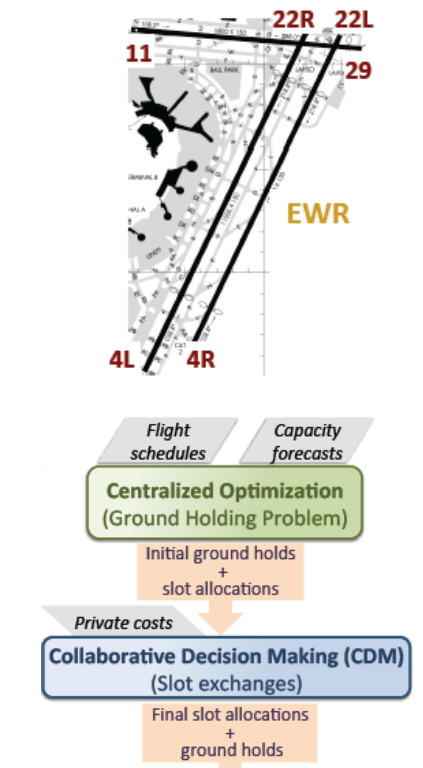
FORCES is developing an integrated resilient design methodology by adopting a rigorous analytical approach to allow the co-design of control and incentive tools. This will enable designers and operators to build-in resilience in CPS by maintaining synergistic integrations of human-centric elements with automated diagnostic and control processes.

Need for Integrating Robust Control & Theory of Incentives

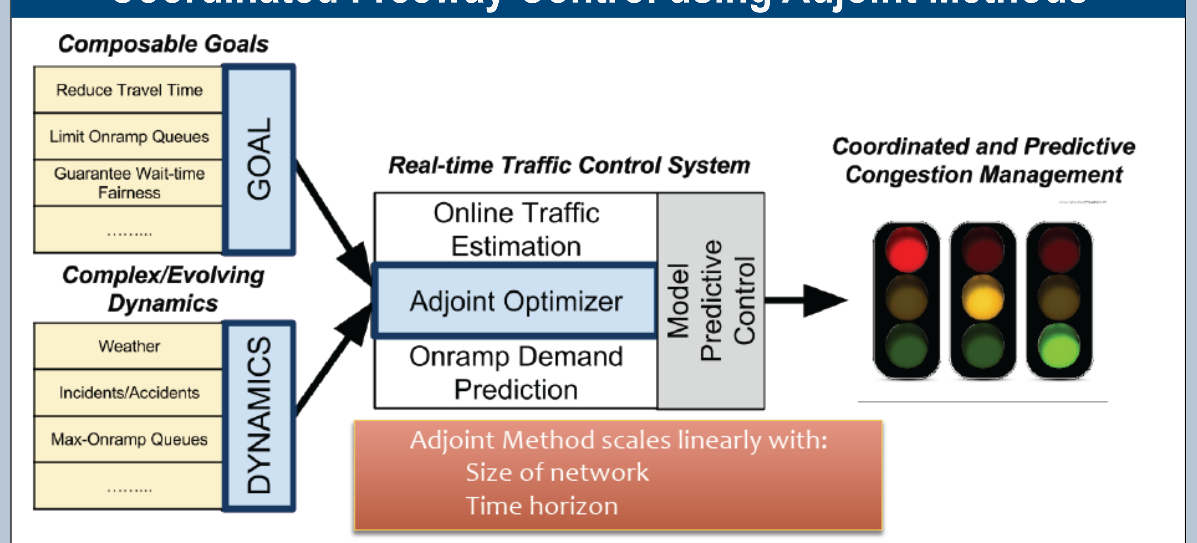


Data-Driven Modeling and Optimization Algorithms for h-CPS

- Multi-stateholder systems
  - Optimization algorithms for resource allocation
  - Incentives for information-sharing
- Approach demonstrated on airport configuration selection
  - Which runways are used for which operations
  - Primary driver of airport capacity

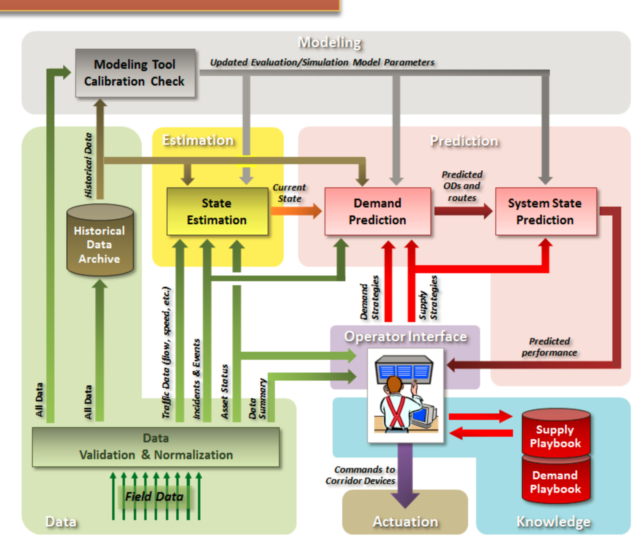


Coordinated Freeway Control using Adjoint Methods

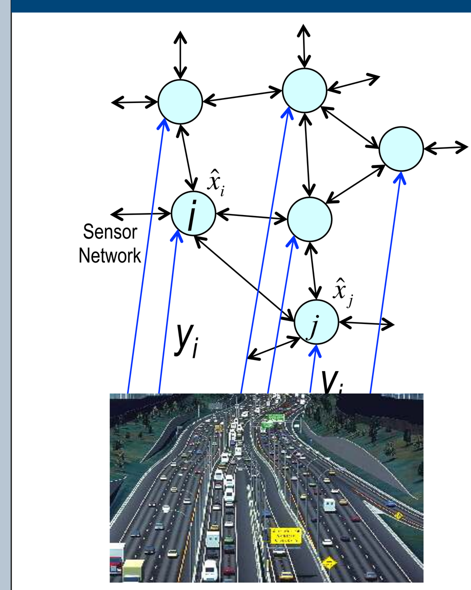


Coordinated networked control using adjoint-based optimization

- Overall reduction of total travel time over existing feedback-based methods
- Robustness to sensor/ prediction noise and model errors



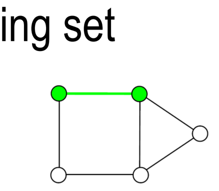
Resilient Distributed Consensus with Trusted Nodes

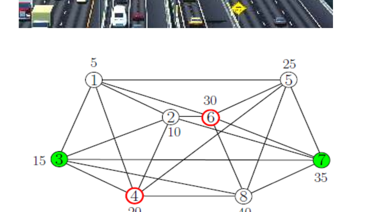


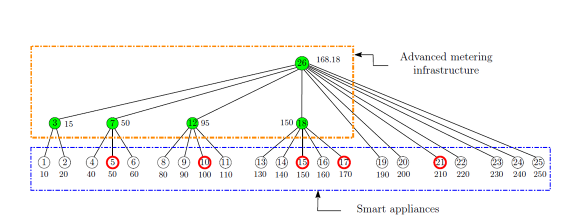
- Minimum variance estimate

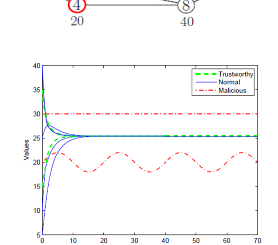
$$\hat{\theta}_{MV} = \frac{\frac{1}{n}\sum_{i=1}^{n}\frac{1}{\sigma_i^2}y_i}{\frac{1}{n}\sum_{j=1}^{n}\frac{1}{\sigma_j^2}}$$

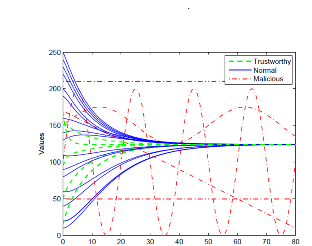
- Trusted nodes form a connected dominating set





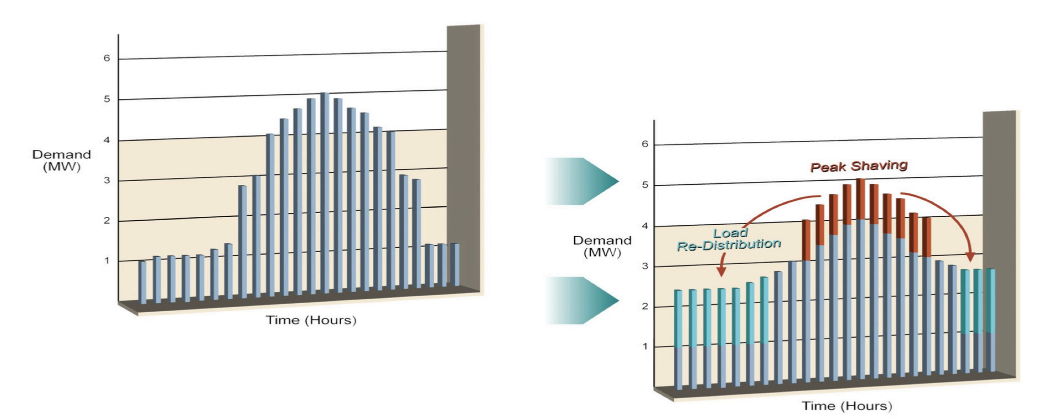






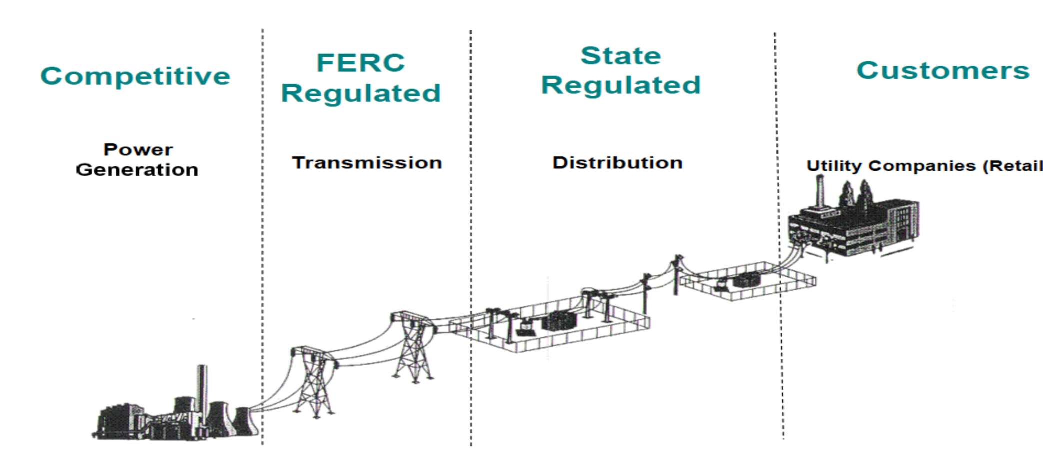
RC + EI for Electricity CPS

Demand management



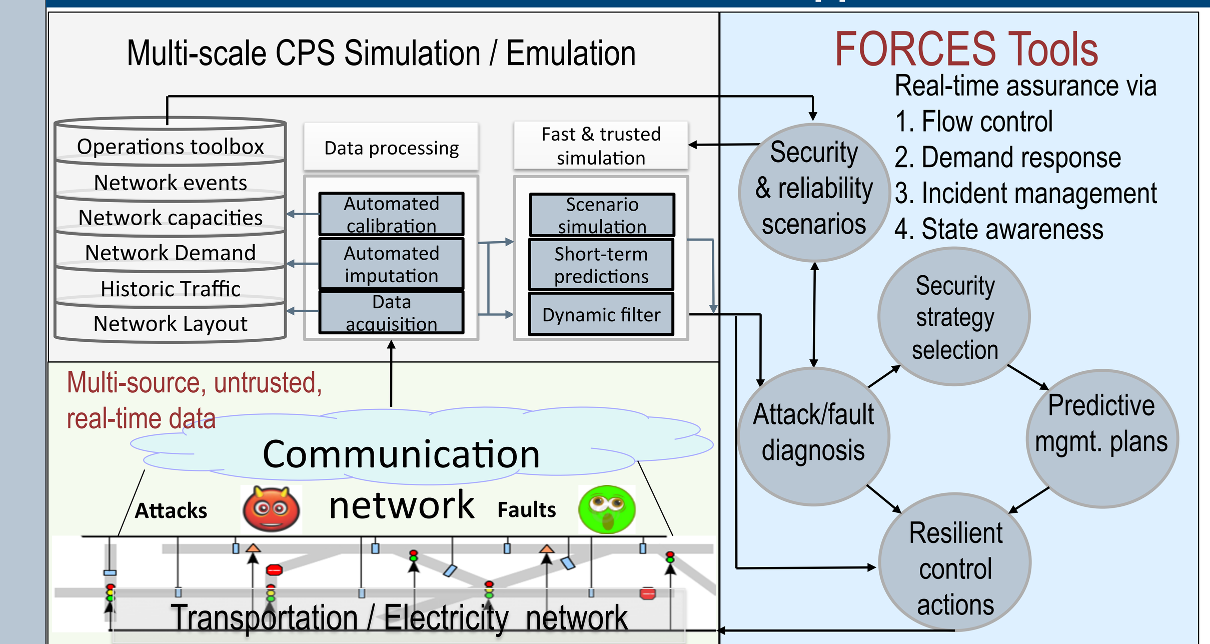
- Reward-based demand response for electricity distribution
- Question: How to incentivize consumers to partly shift/reduce demand?
- Ideas from economics of public good provisioning
- Incentive mechanism: Randomized reward (lottery)
  - user participation is voluntary
  - expected reward of a participating user is proportional to his contribution to the total public good (total shifted demand)
  - users and utility share risks of demand variability (in contrast to real time pricing where risk of demand fluctuations is shifted to users)
  - each user bears risk when it is the cheapest for him
  - both consumers and distribution utility are strictly better off using / employing the incentive mechanism

Electricity Pooling Markets



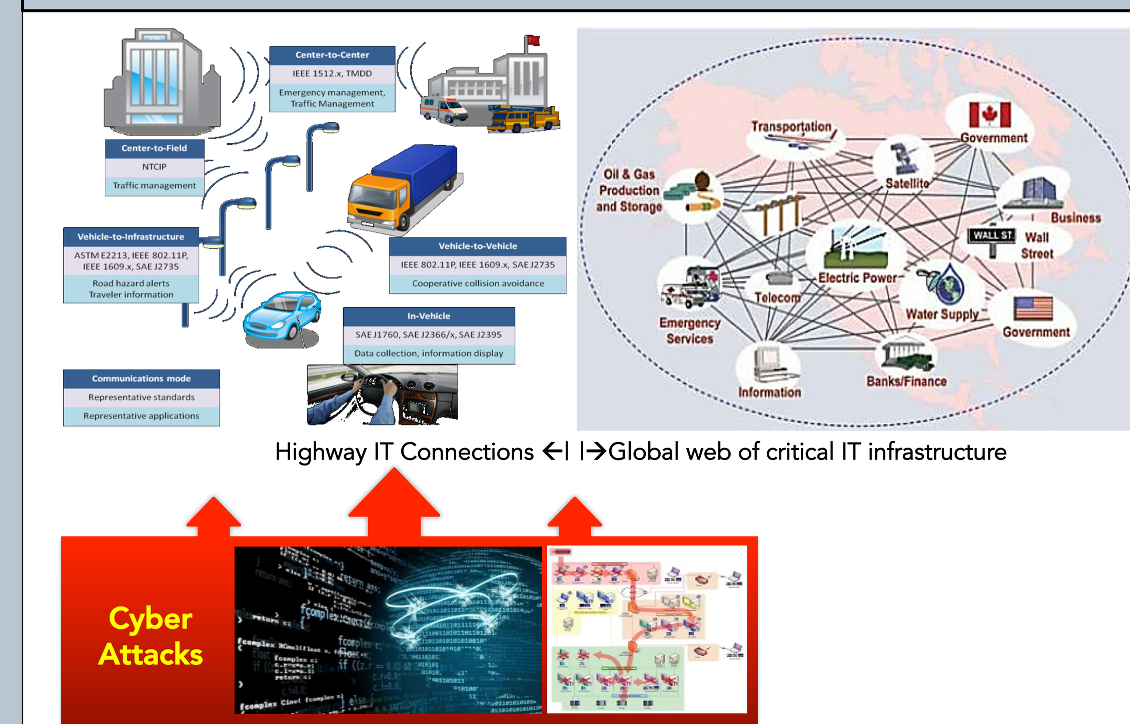
- Market mechanism for electricity pooling markets
- With strategic producers possessing asymmetric information
- Mechanism overview
  - Pooling market with N strategic producers and 1 non-strategic demand
  - Producers are strategic with private information and exercise market power
  - We designed a mechanism that implements optimal social welfare under Nash equilibrium concept
  - The mechanism is individually rational, price efficient and budget balance
  - Every producer report's one price and one production value.
  - Price at equilibrium is marginal cost of production
  - Implementation of the mechanism requires iterative exchange of messages

Evaluation and Validation Approach

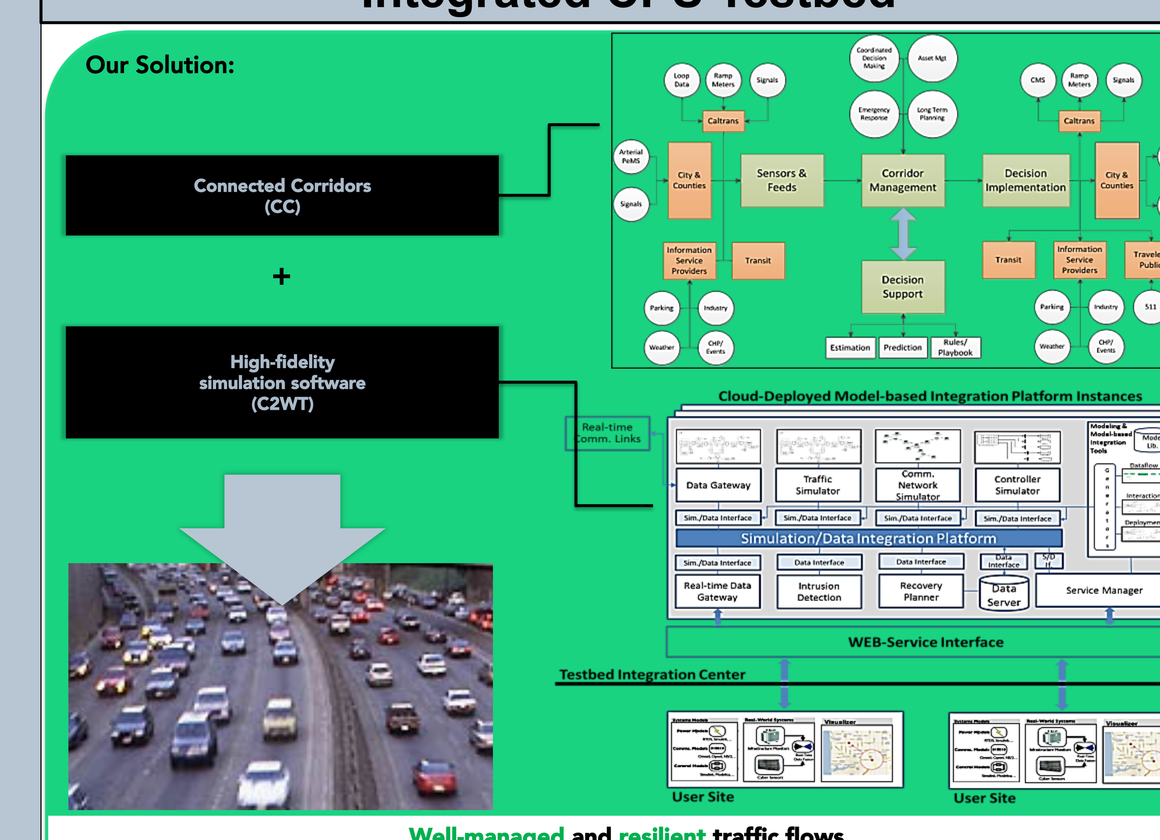


SmartRoads Testbed

Vulnerable Communication and Control



Integrated CPS Testbed



- Off-line use cases
  - High-fidelity simulation of road traffic, based on real data
  - Development and evaluation of novel control algorithms – before they are applied
  - Study of cyber effects on the networks and on the system
  - Training of system operators in preparation for emergencies
- *On-line use cases*
  - Real-time monitoring of traffic and predictive simulation
  - Real-time control of traffic by ramp metering
  - Real-time situational awareness about the status of the network