USC University of Southern California

CPS: Synergy: Cyber Physical Regional Freight Transportation

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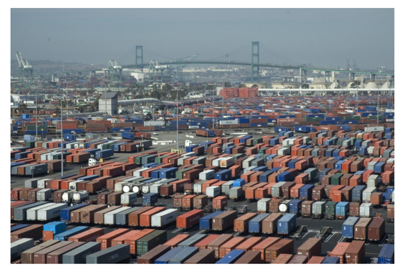
Motivation and Objective

Motivation

- Current Transportation Systems are dynamic, nonlinear with complex interconnections, multimodal and highly unbalanced in space and time with high peak and low peak traffic.
- Routing freight in such an environment based on available traffic information often leads to congesting routes that initially appeared as shortest travel time routes contributing further to unbalancing of traffic loads and to congestion
- Cyber physical load balancing techniques need to be developed for better managing traffic in multimodal networks by balancing traffic in space and time.

Road

Port

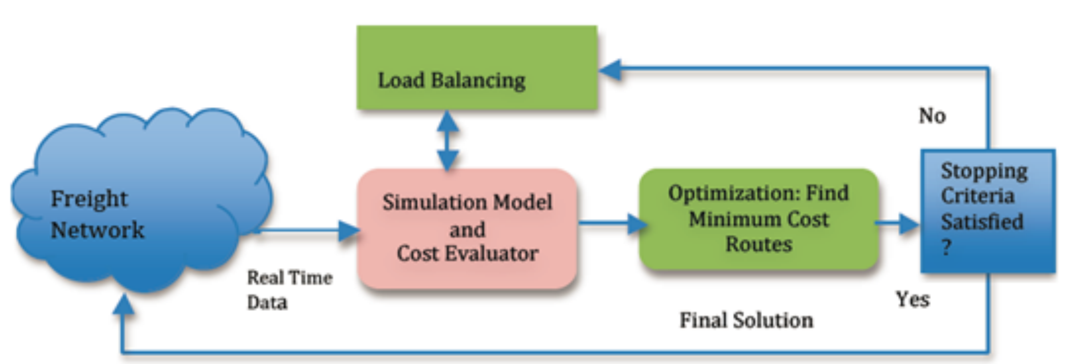


Rail

Project Objectives

- Develop the theoretical foundations of a new control approach referred to as COSMO (CO-SiMulation Optimization) within the CPS framework that uses on line data-driven simulation models to capture complex dynamics of the physical system and provide state estimates to optimization algorithms which generate decisions for control actions in a feedback loop manner.
- Apply the COSMO approach to solve the dynamic multimodal freight routing problem by achieving load balancing in a multimodal transportation system
- Develop a cyber physical coordination system which generates routes for individual users by optimizing a system cost and establishing incentives for participation using game theoretic analytics
- Investigate how identified barriers and policy issues/incentives can be incorporated as mathematical constraints in the optimized dynamic freight load balancing system
- Assess the effectiveness and feasibility of implementing freight load balancing strategies to increase the efficiency and sustainability of urban freight movements by interacting with participating stakeholders.
- Integrate the research results to the University educational program

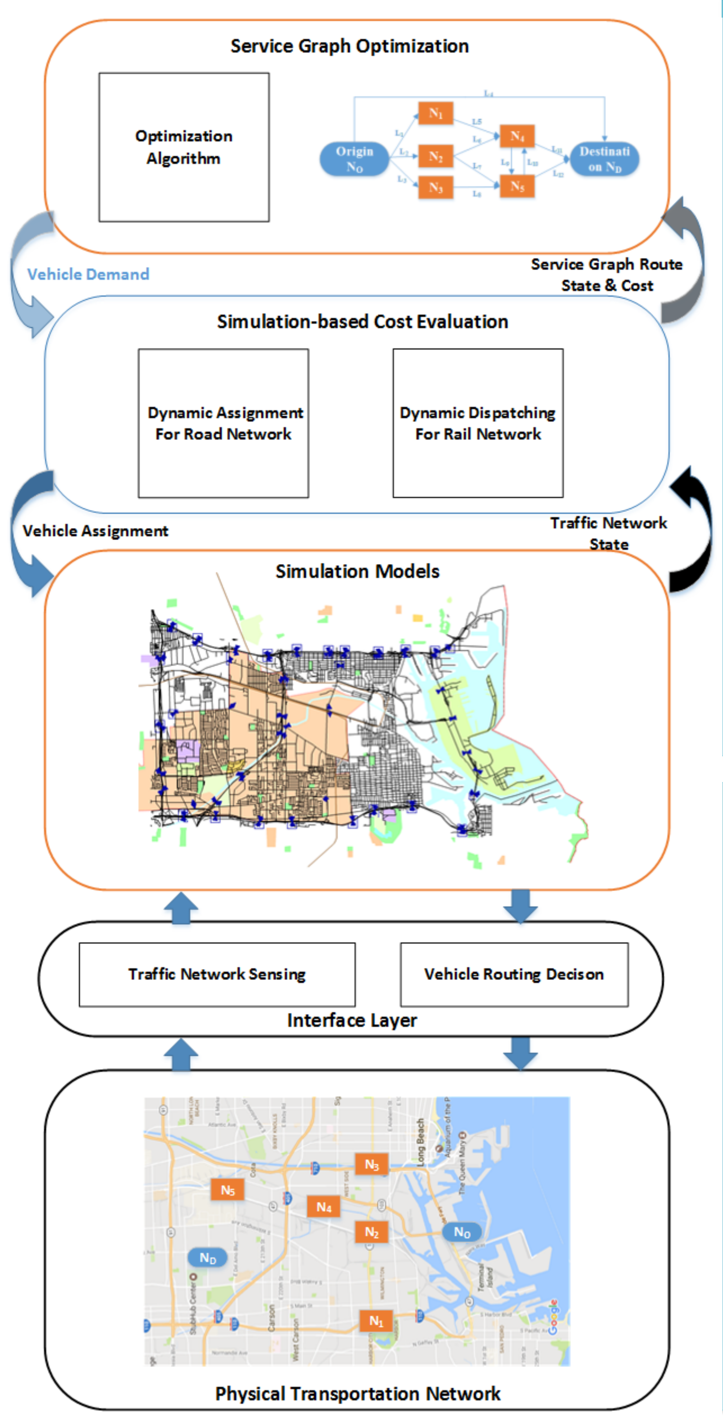
Proposed COSMO Approach



- *Network Simulation Models* describe the dominant characteristics of the real network system and predict states and conditions of the network
- *Optimization Block* uses the predicted network states to generate optimal solution based on minimizing certain objective cost function.
- *Load Balancing Block* generates the control actions for load balancing along different routes.
- *The Stopping Criteria* includes stopping criteria for the iteration process.

COSMO Approach Application

A Hierarchical Design for Multimodal Freight Routing System



Problem Definition

Problem:
How to optimize freight flows of the participated shippers across the multimodal transportation network

Objective:
Minimize total cost consisting of vehicle usage costs and travel time values

Constraints:
Demand conservation
Vehicle availability among service nodes
Vehicle capacity of different traffic modes (railway trains, road trucks, etc.)

Algorithm:
Augmented Lagrangian method to relax complex vehicle constraints;
Solve the relaxed problem by COSMO

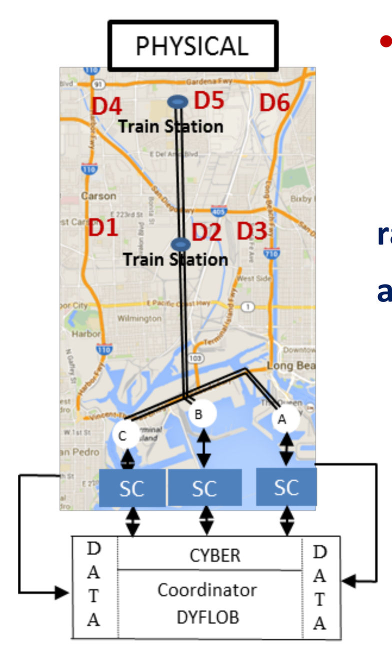
Solving Procedure

Initialization: Set up an initial solution;
Service Network Updating by executing simulation models with current solution;
Optimization: Search new routes with minimum marginal cost based on updated network state and construct an auxiliary solution X_{Aux};
Convergence Check;
Perform Load Balancing: Generate new solution by selecting a step size α

$X^{(new)} = \lambda(\ldots) + \alpha(X_{Aux} - X^{(cu\ldots)})$

(Candidate methods of selecting α: MSA, Optimal Step, Shipper prioritized method etc.)

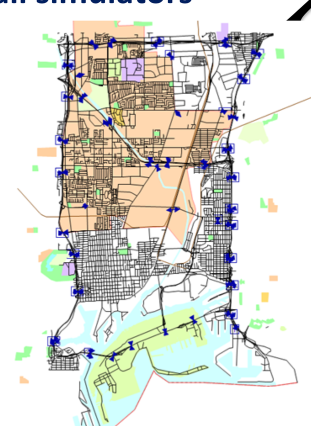
Computational Experiments

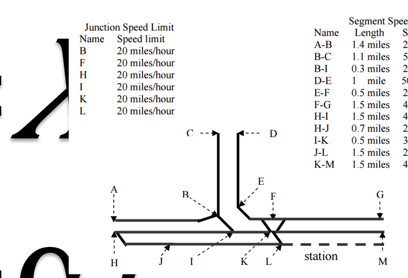


- *Cyber Physical Network - Testbed*

About 80 square miles near the Port of LA/LB

Road network simulator with VISUM plus a discrete event-based rail simulator with Arena. Real historical traffic data are used in road and rail simulators



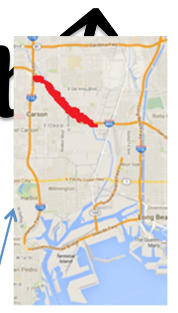


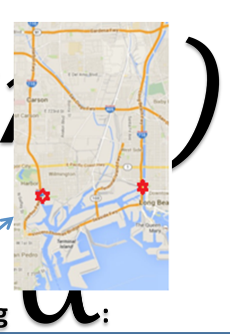
- *Prioritized Load Balancing*

Custom methods such as Method of Successive Averages (MSA),

Optimal Step Size treat all shippers equally.

Give priority to shippers with larger cost standard deviations of the used routes could speedup the algorithm convergence.



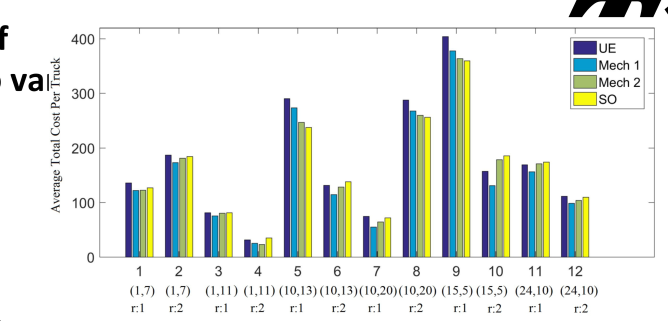


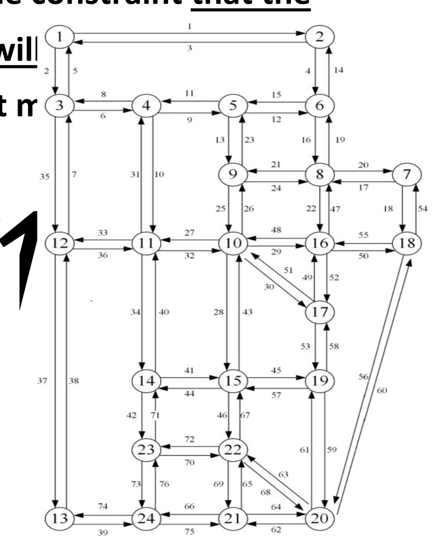
Traffic Condition	MSA with Priority		Optimal Step		Optimal Step with Priority	
	Avg. cost (dollar)	*Time (sec)*	*Avg. cost (dollar)*	*Time (sec)*	*Avg. cost (dollar)*	*Time (sec)*
Normal Traffic	48.34	28810	48.02	4051	48.39	[illegible]
Congested Traffic	65.61	50571	66.34	8647	66.43	5214
I405 Congested	48.62	38651	48.35	2345	48.61	1824
Lane Closures	66.20	39900	67.04	6305	67.13	5441

Game Theoretic Formulation and Results

- *Formulate Freight Routing as a Game Theoretic Model*
- Use of a static non-atomic, symmetric information game theoretic model assuming a stochastic demand vector for the truck drivers while the coordinator knows the actual demand vector.
- The truck drivers are considered to be the "players" of the game and their objective is to minimize their own cost.
- Coordinator provides routing instructions to players by minimizing a "social cost function".
- Coordinator provides incentives for participation by rewarding players whose individual cost is negatively affected and by receiving fees from those who gain, leading to an average zero budget balanced mechanism.
- *Propose and Analyse Four Different Mechanisms*
- User Equilibrium (UE): The truck drivers make uncoordinated selfish routing decisions assuming that they anticipate correctly the behaviors of the other truck drivers. In this case we have a situation called User Equilibrium with a corresponding cost T^{UE}.
- System Optimal (SO): The coordinator does not provide incentives for participation and the users follow the coordinator's decisions even if they lose. The lowest total social cost is denoted by T^{SO}.
- Mechanism 1 (M1): The coordinator provides incentives for participation. If participation is 100%, the coordinator minimizes the social cost function subject to the constraint that the expected cost of the truck drivers under the mechanism suggestions will ... they follow the UE. This mechanism is always efficient and fair since it m... T^{M_1}.
- Mechanism 2 (M2): The coordinator provides incentives for participation. If participation is partial, the coordinator minimizes a weighted sum of the social cost function and a measure of unfairness. Under this mechanism, compliance becomes a Nash equilibrium and there is strong voluntary participation ex-ante (before truck drivers learn the actual demand vector). The corresponding cost is T^{M_2}.
- In terms of efficiency, it holds: $T^{SO} \leq T^{M_1} \leq T^{M_2} \leq T^{UE}$.

- *Application to the Sioux Falls network*
- We assume that the trucks have only 6 possible OD pairs: (1,7), (1,11), (10,11), (10,20), (15,5), (24,10).
- The demand takes one of the following two equi-probable values:
  r:1 (3, 5, 6, 2, 12, 3)
  r:2 (4, 2, 4, 15, 5,2).





Ongoing and Future Work

- *Scalability Issue:* Investigating efficient problem decomposition & parallel execution methodologies that could handle large scale networks, increased demand, etc.
- *Time Window:* Add problem constraints of pickup and delivery time windows. The time window constraints will reduce the solution space significantly but increase the problem complexity and require new solving techniques, especially for large scale problems.
- *Game Theory Employment:* study monetary incentive mechanisms and schemes for freight delivery participants to achieve coordinated optimum assuming a dynamic network with discrete time windows. A special emphasis will be given on budget balance, voluntary participation and truthfulness condition.

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