CPS: Medium: Collaborative Research: Smart Freight Transportation with Behavioral Incentives

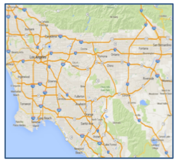
PI: Petros A. Ioannou, Co-PI: Maged M. Dessouky, Genevieve Giuliano

MOTIVATION

- Traffic congestion on the U.S. highways annually costs the trucking industry more than $63 billion in operating expenses, including 996 million hours of lost productivity
- Shippers and other actors in the supply chain operate independently leading to system inefficiencies and unbalanced network in space and time
- There is no incentive to operate in a way that minimizes the impact of freight trucks on traffic

Transportation Network

Freight

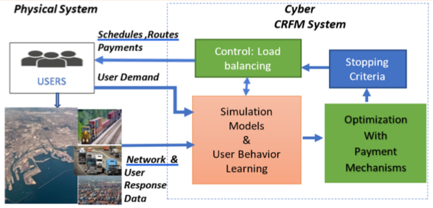


Los Angeles Metropolitan Area

PROJECT OBJECTIVES

- Develop the theoretical foundations of SCOBE for a Coordinated Regional Freight Management CRFM system which generates schedules, routes and payments for freight.
- Develop a two time scale approach where the initial freight schedules, routes are generated by SCOBE approach and then updated according to real-time network status.
- Develop payment mechanisms in time and space in a way that maximizes user utility functions while minimizing a social cost function and motivates the shift of freight loads away from congested areas.
- Use machine learning techniques to study user behavior over time and update user utility functions based on response data to the generated schedules, routes and payments.
- Investigate stability, convergence, robustness and scalability issues of the SCOBE approach.
- The SCOBE approach will be validated with Los Angeles/Long Beach simulation testbed and tested with Ventura Transfer Transport. Company.

PROBLEM FORMULATION



- Develop a co-Simulation Control and Optimization with BEhavioral incentives (SCOBE) approach
- Simulation models are used to generate/predict the dependencies of the link states on time, space and added loads
- Utility functions for each user are established and updated based on new data
- Payment incentives are used by the cost minimizer and load-balancing controller that leads to a lower cost

INCENTIVES

$$\underset{\alpha(\cdot),p_j(\cdot)}{\text{minimize}} \quad \lambda E\left[T_S(\alpha)\right] + (1-\lambda)\Phi(\alpha,p)$$

$$\text{subject to} \quad E\left[\sum_{r\in R_j} \alpha_r^j \bar{J}(r,\alpha) + p_j(d)/d_j\right] \le \min_{r\in R_j} E\left[\bar{J}(r,\alpha)\right]$$

$$E\left[T_{tr}(\alpha(d))\right] \le E\left[T_{tr}^{\text{UE}}\right]$$

$$\sum_{r\in R_j} \alpha_r^j = 1,\ \alpha_r^j \ge 0,\ E\left[\sum_j p_j\right] = 0,$$

- Minimization of a weighted combination of the expected total travel time of the network and of a fairness measure
- Provide incentives in collective level by ensuring that the total travel time of the truck drivers under the mechanism will be less than in the case of the UE
- Provide incentives in the individual level by ensuring that every truck driver will be better-off compared to the UE
- Make the coordination mechanism to be budget balanced on average
- Guarantee the existence of a feasible solution
- Above formulation to be modified to include utility function constraints

DISTRIBUTED TRUCKING ROUTING SYSTEM

- ***Problem Description***

To assign a number of demands from origins to destinations with considerations of several factors: *time window*, *road network traffic condition*, *emissions*, etc.

- *Time window*: pick up time window, delivery time window
- *Road network traffic condition*: Vehicle Travel Time
- *Emissions*: CO_2, $PM_{2.5}$, NO_x

- ***Formulation***

$$\min TC(X) = \sum_{k\in K}\sum_{i\in I}\sum_{j\in J}\sum_{r\in R_{i,j}} S_{i,j}^r(k) X_{i,j}^r(k)$$

$$= \sum_{k\in K}\sum_{i\in I}\sum_{j\in J}\sum_{r\in R_{i,j}} \left(C_{i,j}^r(k) + \theta^r T_{i,j}^r(k)\right) X_{i,j}^r(k)$$

subject to:

$\sum_{k\in K}\sum_{r\in R_{i,j}} X_{i,j}^r(k) = d_{i,j}, \forall i\in I, \forall j \in J$ (1)

$\sum_{i\in I}\sum_{j\in J}\sum_{r\in R_{i,j}}\sum_{\tau\le k} X_{i,j}^r(\tau)\delta_{l,\tau,k}^r = x_l(k), \forall l\in L, \forall k\in K$ (2)

$0 \le x_l(k) \le u_l v_l(k), \forall l \in L^R, \forall k \in K$ (3)

$X_{i,j}^r(k) \ge 0, \forall i\in I, \forall j\in J, \forall k \in K$ (4)

- ***Methodology***

1. Relaxed Problem
   $\min TC(X) + \sum_{k\in K}\sum_{l} \sigma_l\, \phi(x_l(k), u_l(k), v_l(k))$
   subject to constraints (1), (2), (4)
2. Check convergence, if not convergent, proceed to step 3, otherwise, terminate the algorithm and output X as the optimal solution
   $\phi(x_l(k), u_l(k), v_l(k)) \le \eta$
3. Increase penalty factor σ_l, proceed to step 1

- Initial feasible solution $X_{ij}^{(0)}$, transfer it into x_l
- Simulate X with road network simulator, output simulated results: travel time, emissions, etc.
- Update marginal cost of links and routes in R_{ij} based on simulatedresults: *travel time*, *emissions*, etc.
- Generate one minimum marginal cost route for each R_{ij}
- Generate augmented X_{aug} based on R_{ij} in the previous step
- Set new X as $X^{(m+1)} = X^{(m)} + \beta(X_{aug} - X^{(m)})$
- Check convergence, if convergent, output X as the solution of relaxed problem,

else, proceed to step 2.

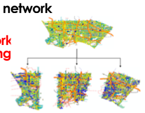
- ***Scalability issue***

Marginal cost update depends on simulated results from road network simulator. However, the time and space complexity grows exponentially with:

- the number of demands
- the scale of road network

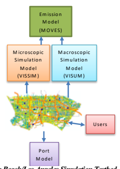
Solution:

- Distributed network
- Parallel computing



EVALUATION/EXPERIMENTATION PLAN

- ***Evaluation***
  - Testbed: Long Beach/Los Angeles simulation testbed
  - Data: Archived Data Management System (ADMS) , transit system, accidents, incidents, highway and arterial traffic data, survey data and SCAG data
  - Components: Port Model, Road Network, Emission Model
  - Traffic simulator: Vissim (Microscopic), Visum (Macroscopic)
  - Plan:
    1. Use existing data sources to generate a truck O-D matrix
    2. Use survey data to examine user and firm behavior
    3. Estimate the utility function
    4. Use SCOBE to estimate the optimal allocation of trips across time windows and routes, and generate associated prices.
    5. Discuss results with stakeholders



Long Beach/Los Angeles Simulation Testbed

- ***Experimentation Plan***
  - A truck transport company, Ventura Transportation, is recruited to participate in a SCOBE demonstration.
  - We will interview the dispatcher and manager to determine how routes are assigned, what factors are taken into consideration in sequencing trips, etc.
  - We will apply the SCOBE approach to generate a "system optimal" solution for the set of O-D pairs over the daily time window
  - We will compare the SCOBE assignment with the dispatcher assignment and analyze the results.
  - The second test is to use the real-time portion of SCOBE to adjust the assigned routes on the fly and determine any savings in travel time and/or emissions.

BROADER IMPACT

Broadening Participation in Computing (BPC) plan:

i) **Engage URM undergraduates in research and motivate to pursue graduate studies**

ii) **Engage URM high school students in STEM higher education and motivate to pursue University degree**

2019 NSF Cyber-Physical Systems Principal Investigators' Meeting
November 21-22, 2019 | Crystal City, Virginia

Award ID#: CNS-1932615