#158 V2V Cooperative Formation Control

Final Research Report

PI: George J. Pappas, Ph.D.

Department of Electrical and Systems Engineering

University of Pennsylvania

Disclaimer

The Problem

In this project, we propose a data-driven dynamic system-wide optimal resource allocation and vehicle formation approach to improve the efficiency of transportation systems under mobility demand uncertainties. The models and methods proposed is applicable to resource allocation problems of other smart city systems when resource is limited and data is available to predict future (uncertain) demand. Both historical and real-time data to predict future passenger demand, and the vehicle formation algorithm aims to improve service efficiency. We use the metric of balanced supply-demand ratio at each region of the city, since more vehicles are allocated towards busy regions along their routes dynamically before busy hours come. The motivation of this work, uncertain demand, and the proposed algorithm framework structure is shown as Figure 1.

The world is getting instrumented with numerous sensors and smart devices, vast amounts of data are available to learn models, and computation devices are smaller, faster, and more accessible than ever before. The fourth industrial revolution is coming, empowered by technologies including cyber-physical systems (CPS, as known as Internet of Things under some context) and robotics. These systems typically involve the tight integration between distributed computational intelligence, communication networks, and physical world. They provide new capabilities to improve quality of life and enabling technological advances in critical areas, such as transportation, energy, healthcare, and manufacturing. Meanwhile, highly interconnected and integrated systems in smart cities pose new challenges and concerns about safety, efficiency and security, due to the increasing complexity and scale, environmental uncertainties, resource limitations, and high expectations of autonomous operation, predictability and robustness. For the first time ever, we have more people living in urban areas than rural areas. To address their emerging challenges in this inevitable urbanization, the White House announces Smart Cities Initiative with $160 million investment in September 14, 2015.

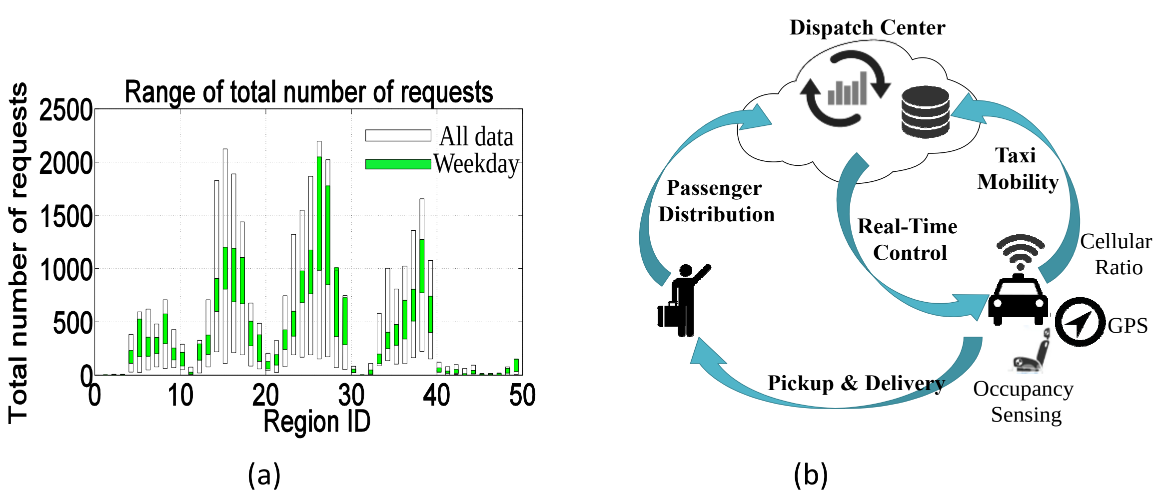


Figure 1. The motivation of this project and the proposed system structure. (a) Total number of requests range during 5-6pm in Manhattan, NYC. (b) The proposed system structure.

Transportation systems are important fields in urban areas and raises challenges for a new generation of vehicle coordination system. Traditional urban transit services either employ suboptimal and fixed components such as schedules and routes, or only apply greedy algorithms that far from optimal. With the development of ubiquitous sensing systems, large-scale multi-source data is collected online with high volume, variety and velocity. However, how to identify and make sense of dynamic relationships between urban-scale phenomena (such as demand and supply of mobility-on-demand systems) based on data to improve the service efficiency of modern transportation systems is still a challenging and unsolved problem.

Our approach

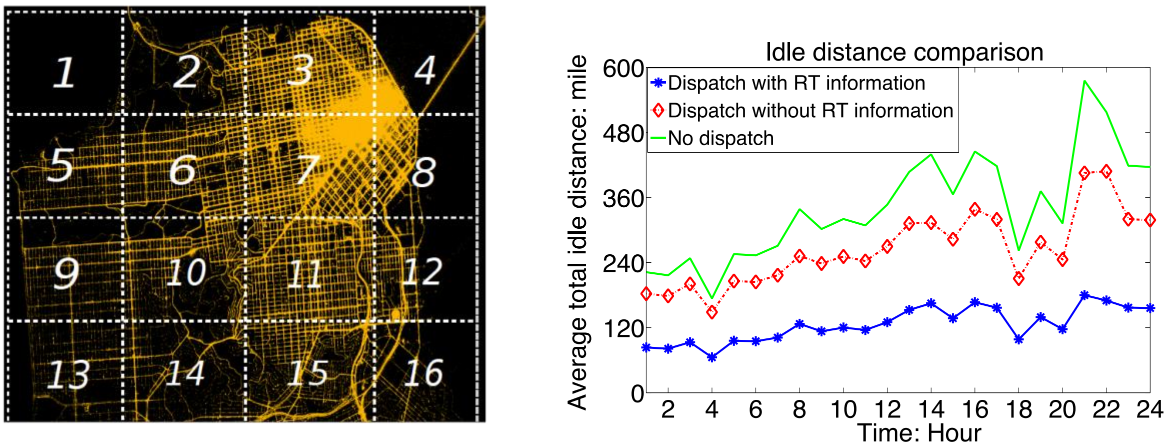
Receding Horizon Control for Real-Time Vehicle Balancing. We first design receding horizon control (RHC) vehicle balancing model that takes advantage of both machine learning method and model predictive control to decide vehicle allocating locations considering both current and anticipated future demand and service costs. We utilize both historical and real-time data to predict future demand, and compute suboptimal dispatch solutions for a system-level globally balanced supply with least associated cruising distance under practical constraints. The goal of a balanced supply-demand ratio at each region of the city improves service efficiency since more vehicles are allocated towards busy regions along their routes dynamically before busy hours come.

Data-Driven Robust Resource Allocation under Demand Uncertainties. However, the model accuracy of predicted demand affects the performance of resource allocation. To consider demand model uncertainties in resource allocation problems such as vehicle balancing in smart cities, we develop a robust optimization model and a corresponding uncertainty set construction algorithm based on data. The robust fair resource allocation method we design solves two main challenges to provide any desired level of probabilistic guarantee for an optimal resource allocation solution of large-scale systems. First, regarding to the usual NP-hard computational complexity of a robust optimization problem, we formulate a minimax fair resource allocation problem that convex of the decision variables and concave of the uncertain parameters, and prove the equivalent ***computationally tractable forms*** with polytope and second-order-cone (SOC) types of uncertainty sets. Second, we model spatial-temporal correlations of the demand uncertainty purely from data, based on hypothesis testing theories without assumptions on the true model of the random demand.

Take the Ambiguity of Probability Distribution of Demand in Real-Time---Minimize the Average Cost. While robust optimization methods guarantee the performances of urban transportation systems under worst-case scenarios, the trade-off between average performances of the systems should not be ignored. However, how to deal with uncertainties in demand probability distribution for improving the average system performance is still a challenging and unsolved task. To minimize the average cost considering spatial-temporally correlated demand probability distribution uncertainties in ***real-time***, we develop a ***computationally tractable*** data-driven distributionally robust vehicle balancing model. We design an efficient algorithm for constructing distributional uncertainty set, and leverage a quad-tree dynamic region partition method for better capturing the dynamic spatial-temporal properties of the uncertain demand.

Findings

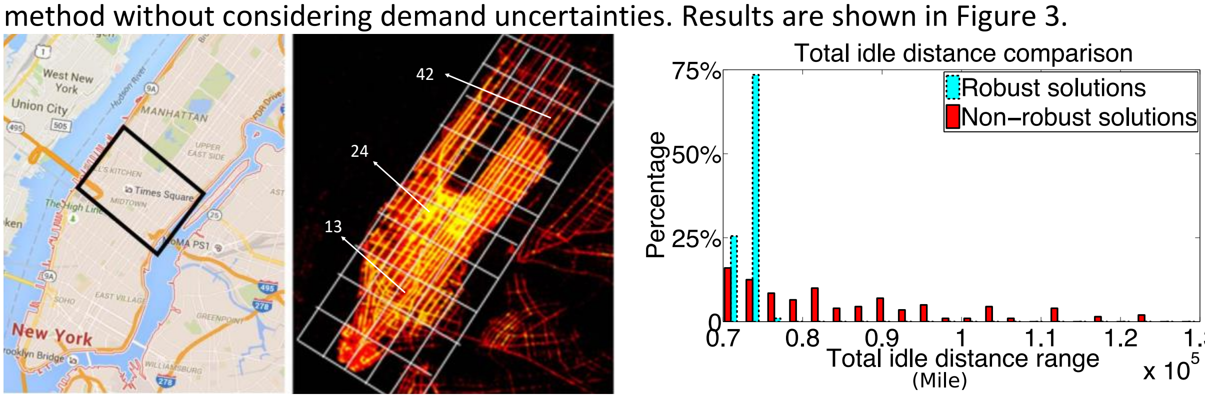
Evaluation results based on a San Francisco dataset support system level performance improvements of our RHC approach and show that the total idle driving distance is reduced by 52% compared with the original historical record as shown in Figure 2.



(a) (b)

Figure 2. (a) Regions partition map of San Francisco City. (b) Idle distance comparison for: the original data without our taxi dispatch algorithm; taxi dispatch algorithm without real-time GPS information; our proposed taxi dispatch algorithm with real-time GPS information and passenger demand predicted based on both historical and real-time data.

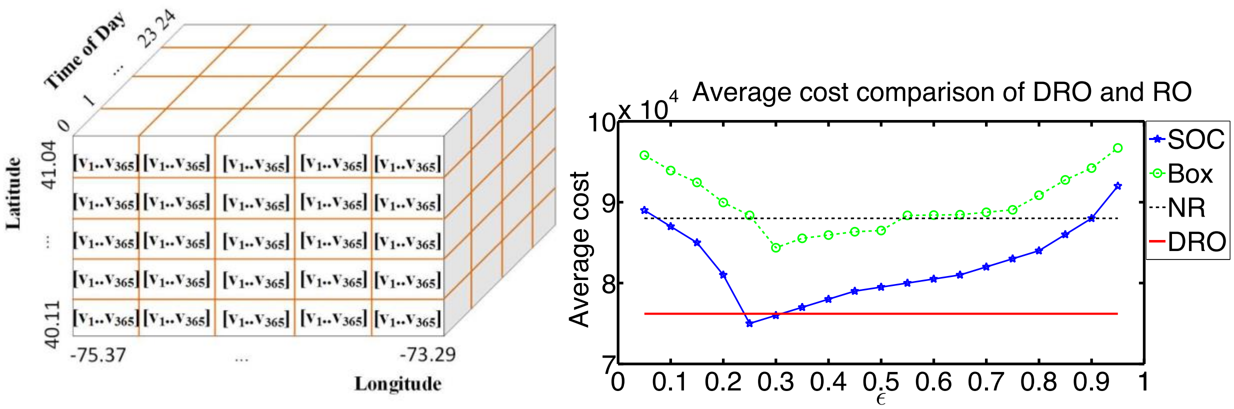
Evaluations based on 100 GB data of New York City's taxi transportation system show that when applying the robust resource allocation method to dispatch taxis, ***the average total idle driving distance is reduced by about 20 million miles annually*** compared with optimal vehicle balancing method without considering demand uncertainties. Results are shown in Figure 3.



(a) (b)

Figure 3. (a) Region partition of Manhattan, NYC. (b) Idle distance comparison of 200 times of simulations for robust taxi dispatch considering predicted demand uncertainties and non-robust solutions without considering demand uncertainties.

We show that the ***average total idle distance is reduced by about 60 million miles*** or the ***gas cost is reduced by about 8 million dollars annually*** for all taxis in NYC, compared with taxi dispatch solutions based on static region partitions without considering demand distribution uncertainties.



(a) (b)

Figure 4. (a) Quad-tree dynamic region partition method. (b) Average cost comparison for four methods: robust resource allocation with second-order-cone (SOC) form of demand uncertainty set and box range type of demand uncertainty set; non-robust resource allocation (NR); distributionally robust demand uncertainty set (DRO).

In summary, we demonstrated that the data-driven resource allocation framework with application to coordinated taxi network formation enables:

- Incorporate large-scale historical and real-time sensing data in demand prediction and control
- Balanced supply towards current and predicted future demand with minimum cost
- Any desired level of probabilistic guarantee of the worst-case cost and expected allocation cost
- Demand uncertainty sets construction algorithms for various machine learning methods
- Significant reduction of total idle distance of all vehicles to satisfy mobility demand in cities

Conclusions

Ubiquitous sensing in smart cities enables large-scale multi-source data collected in real-time, poses several challenges and requires a paradigm-shift to capture the complexity and dynamics of systems. Data-driven cyber-physical systems (CPSs) integrating machine learning, statistical methods, optimization, and control are highly desirable for this paradigm-shift, since existing model-based techniques of CPSs become inadequate. For instance, how to identify, analyze the dynamical interplay between urban-scale phenomena (such as mobility demand and supply) from data, and take actions to improve system-level service efficiency is still a challenging and unsolved problem in transportation systems. In this talk, we present a data-driven dynamic robust resource allocation framework to match supply towards spatial-temporally uncertain demand, while seeking to reduce total resource allocation cost. First, we present a receding horizon control framework that incorporates large-scale historical and real-time sensing data in demand prediction and dispatch decisions under practical constraints. However, demand prediction error is not negligible and affects the system's performance. Therefore, with spatial-temporal demand uncertainty models constructed from data, we then develop two computationally tractable robust resource allocation methods to provide probabilistic guarantees for the system's worst-case and expected performances. As a case study, we evaluated the proposed framework using real taxi operational data.