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Constrained System-Optimal Route Planning in support of Fleet Route Planning, Ridesourcing, and Ridesharing

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Research Needs

Motivation: Route (or path) planning is a core optimization problem to address for efficient and intelligent transportation in various transportation systems, form Advanced Traveler Information Systems (ATIS) to Transportation Network Companies (TNCs) to Fleet Management Systems. In the past, numerous route planning solutions are introduced by the research community and adopted by industry products (e.g., vehicle navigation devices, and online map services such as Google Maps®) to address this need. Nowadays, such products have become hallmark of ITS in the general public's view.

While the literature on algorithms and systems designed for efficient and accurate route planning in large-scale transportation networks is extensive (see the Related Work Section below), to the best of our knowledge all existing solutions focus on planning optimal routes for *individual travelers*. With this approach, "optimality" is defined based on a criterion (or criteria, in case of multi-criteria route planning) that captures best interest(s) of individual travelers (e.g., fastest route, shortest route, most scenic route, etc.) rather than those of the transportation network/system as a whole. Accordingly, each route is planned in a so-called "selfish" manner for each individual traveler without concern of how this might affect the overall utility of the transportation network for all travelers. Although popular, this definition of optimality is not necessarily aligned with the strategic goals of the USDOT, which demand optimal utilization of the transportation network in terms of performance measures such as mobility/throughput, overall travel quality, overall safety, and overall environmental sustainability.

With our previous MPC project, we addressed this misalignment by introducing *system-optimal* route planning, an alternative approach to route planning where optimality of the routes is defined based on their impact on overall utilization of the transportation network rather than benefits of individual users [1]. While the advantage of system-optimal route planning was previously known to the research community, lack of scalable solutions for implementation of this approach at practical scales (e.g., city-level route planning) had rendered this approach impractical. With our prior work, we have introduced system-optimal route planning solutions that leverage two big data methodologies, namely, *guaranteed approximation* and *distributed and parallel computation* to scale up system-optimal route planning for practical applications.

With this proposal, we plan to extend our system-optimal route planning solutions to consider scenarios where certain user constrains ought to be enforced for valid system-optimal route planning. In particular, these scenarios include system-optimal route planning for *fleet route planning, ridesourcing* and *ridesharing*. In the remainder of this section, we first review the related work and our proposed work on route planning in these scenarios. In the subsequent sections, we further elaborate on our proposed plan to extend our system-optimal route planning solutions in support of these transportation planning scenarios.

<u>Related Work and Proposed Work</u>: A comprehensive survey of general solutions for route planning in transportation networks is provided by Delling et al. [2] and more recently by Bast et al. [3]. Here, we review the route planning literature on the three focus scenarios considered in this proposal, and correspondingly discuss our proposed work to develop constrained system-optimal route planning solutions in each case:

A. *Fleet Route Planning*: Fleet management systems allow numerous companies which rely on transportation in business (e.g., delivery companies such as FedEx) to remove or minimize the risks associated with vehicle investment, improve efficiency and productivity, and reduce overall transportation and staff costs. In particular, fleet route planning is one of the main functionalities provided by fleet management systems, which focuses on optimization of the fleet vehicle routes while they provide the services offered by the company. For example, fleet route planning is used by delivery companies to schedule the trips and stops their fleet vehicles need to make for delivery on a daily basis.

   While the market is populated with fleet route planning tools (e.g., Route4Me [4], Viamente [5], Nextraq [6], and Routific [7]), the main objectives of all these tools is to meet the constraints defined by the required services (e.g., the time and location for each parcel delivery), while they largely disregard optimal utilization of the transportation network. However most companies that use fleet management systems, and in particular fleet route planning, are required to comply with government legislation (duty of care) in terms of overall emission as well as energy consumption to ensure environmental sustainability. With this proposal, we intend to develop a system-optimal fleet route planning solution which not only meets the service constraints of the fleet, but also optimizes utilization of the transportation network to enhance mobility, emission, and energy footprint of the fleet.

B. *Route Planning for Ridesourcing*: Ridesourcing companies (also called Transportation Network Companies or TNCs) such as Uber, Lyft, and Sidecar, are organizations that pair passengers via websites and mobile apps with drivers who provide transportation services. These companies are different from fleet-based companies, because the set of vehicles they manage is dynamic and autonomous. TNCs are examples of the sharing economy and shared mobility, and nowadays have a significant impact on transit in urban areas [8]. The main goal of route planning for ridesourcing is to develop so-called *driver-passenger matching schedules* in real-time, which similar to fleet route planning is largely concerned about identifying the optimal set of matches to reduce the driver detour and passenger pickup time for each trip [9].

While unlike fleet-based companies, currently TNCs are not subject to government legislations on emission and energy consumption of the vehicles serving their passengers, given the existing pilots in a few US cities [10], they are expected to either augment or replace their drivers and vehicles with self-driving cars in near feature (e.g., see [11]). In such a case, the current driver-passenger matching algorithms that merely satisfy the driver and passenger constraints will be insufficient. To address this gap, we propose developing constrained system-optimal route planning solutions for ridesourcing that not only consider the typical driver and passenger constraints, but also enable optimizing the energy and emission footprint of the cars to meet the government requirements (note that with self-driving cars, TNCs will be categorized as fleet-based companies, and therefore, subject of the same government regulations) while optimizing the cost of the TNC operation.

C. *Route Planning for Ridesharing*: Jacobson and King [12] have shown that adding one passenger to every 10 traveling cars would potentially save 7.54-7.74 billion gallons of fuel per year. Thus, ridesharing, which is the shared use of a car by its driver and one or more passengers/riders, is a viable solution for congestion, excessive energy consumption and air pollution due to transportation; hence, an important approach to achieve environmental sustainability and ensure livable communities. Currently, there are many operational ridesharing services and the demand for these services has increased sharply in recent years. The growing ubiquity of the internet enabled mobile devices even enables practical dynamic ridesharing [13], where the process of matching the riders and drivers to form ridesharing is done on very short notice or even en-route [14].

Alike regular route planning solutions, all existing algorithms for matching drivers and riders for ridesharing (e.g., [15]) focus on planning optimal routes for the individual travelers that take a ride; hence, non-system-optimal. In this proposal, we plan to develop a system-optimal solution for ridesharing that enables optimal utilization of the transportation network for ridesharing. Unlike our prior work on system-optimal route planning, where there is no constraints to enforce, with ridesharing we need to consider a variety of user choices/constraints in sharing a ride (e.g., drivers' choices in deviating from their regular paths, or riders' choices on type of the vehicle, sex of the driver, etc.); hence, *constrained* system-optimal route planning is required for ridesharing.

Research Objectives

With this proposal, we will:

1. Design three constrained system-optimal route planning solutions, one for each of the three focus scenarios of this proposal (i.e., fleet route planning, ridesourcing, and ridesharing), considering the specific family of constraints in each scenario;
2. Develop a data-driven simulation testbed (based on realistic road network and traffic data) to implement and evaluate all the designed route planning solutions;

3. Perform simulation-based comparative analysis to performance of the proposed route planning solutions to those of the state-of-the-art route planning solutions in each of the three aforementioned scenarios;
4. Advance knowledge by reporting results of the comparative analyses;
5. Advance policy and practice with respect to transportation network utilization;
6. Advance education through the training of students; and
7. Build an evidence base by disseminating findings through publications and presentations.

To elaborate, we plan to build on our prior work and extend our existing system-optimal solutions by incorporating the scenario-specific constraints described in the previous section to develop the constrained system optimal solutions for each of the three focus scenarios, i.e., fleet route planning, ridesourcing, and ridesharing. We will also extend our existing simulation testbed to implement our proposed constrained system-optimal solutions as well as the related work for comparative analysis and evaluation. The results of this study will be presented in relevant courses offered by the PI (e.g., CSCI Big Data Mining and Analytics and CSCI Big Data Systems), and disseminated through research publications and presentations. The PI will also leverage his existing connections with relevant industry partners (e.g., FedEx, Uber and Lyft) as well as federal and state agencies (CDOT and NREL) to explore technology transfer and policy impact opportunities based on the results of this study.

Research Methods

Below, we will review our proposed methodology toward achieving the aforementioned objectives, where applicable:

<u>Designing Constrained System-Optimal Route Planning Solutions</u>: To develop our existing system-optimal route planning solutions, while we learned from the past literature on optimal route planning [2, 3], our main new challenge was that a system-optimal solution optimizes a *holistic* measure (i.e., the network utility function) that frequently changes by any change of utilization in the entire network, whereas previous route planning solutions could simply rely on local measures of performance (e.g., fastest route). In turn, using a holistic measure for optimization is complicated as its real-time computation based on massive data poses a Big Data challenge, particularly, limiting the scalability of any approach that attempts to derive a system-optimal solution. As mentioned before, we used two orthogonal big data methodologies, namely, *guaranteed approximation* and *distributed and parallel computation*, to address this challenge and developed scaled-up system-optimal route planning solutions for practical applications [1].

To develop the *constrained* system-optimal solutions targeted in this proposal, we build on our prior work that allow for scaled-up system-optimal route planning. However, here our new major challenge is to effectively incorporate various types of constraints in these solutions such that the proposed solutions remain scalable. Toward this end, we will first learn from the exiting literature on relevant *transportation scheduling problems* [16-18] (such as service planning, timetabling, vehicle scheduling, etc.) that focus on constraint satisfaction, to develop hybrid system-optimal routing-scheduling solutions that not only satisfy the constraints of our focus scenarios but also follow a system-optimal approach for route optimization. However, we believe incorporating new constraints for system-optimal route-planning can further increase the complexity, and hence, decrease the scalability of the solutions. Therefore, second we will further enhance our existing approximation and parallelization based solutions to maintain the scalability of the proposed solutions.

Data Collection and Generation: To enable our simulation-based evaluation of the proposed constrained route planning solution, we need (road) network data and traffic data as well as service request data (e.g., ridesharing and ridesourcing requests, fleet service plans). We will obtain real road network data from TIGER dataset [19]. For traffic data, we will use an existing traffic data generator (e.g., MNTG [20]) to generate the traffic data we need. Many of the existing traffic data generators are open source and allow for fine tuning of the data generation process, if the parametrized interface of the data generator does not provide sufficient flexibility to generate the type of data we need. In addition, Dr. Banaei-Kashani is currently working with Colorado Department of Transportation (CDOT) toward developing the CDOT big data infrastructure, which is expected to host all real data (including traffic data) collected by CDOT. Accordingly, Dr. Banaei-Kashani is planning to further explore opportunities to obtain real traffic data from CDOT through this connection, once/if this grant is awarded. It is important to note that such real data will be complementary to the synthetic data we will generate, but not required; while the former can show applicability of the solutions in a specific real-world scenario, the latter allows extensive evaluation of the solution by providing full control on determining the data characteristics. Finally, we plan to obtain and/or generate service request data as follows: 1) for fleet route planning, we will use open data from OpenAddressies.io [21] to identify geocoded address data and use randomization to generate location and time for service requests; 2) for ridesourcing, we will obtain data from Uber Movement [22] and infer realistic ridesourcing service request data; 3) for ridesharing, we will use the available travel data and models from drcog [23] and use a randomized approach to select trip and ride request data.

Simulation Testbed: Previously, we have developed our own in-house simulation testbed for system-optimal route planning, we plan to use and extend this testbed to evaluate the proposed solutions in this proposal. Our testbed is built around the MATSim agent-based transportation simulator. Event hooks allow for the control integration and analysis of different simulation states. MATSim was also chosen due to its long-standing position in vehicle simulation (since 2004) as well as it's active support community. As MATSim is written in Java, we were motivated to select a language for development with Java interoperability, and thus we chose Scala, for its succinct and functional style, as well as its success in solving large-scale, distributed compute problems (Scala is the language responsible for Apache Spark and Kafka). The testbed has three major components: a population module, a test runner module, and a routing algorithm module. Populations are generated and managed as a series of time-ordered requests, with utilities for random generation across a generic road network. The test runner is designed to iterate over time batches and apply a given routing algorithm, while managing the interoperation with MATSim. The routing algorithm itself will be either a normal, Google-like routing algorithm, or one of our system-optimal routing solutions in test, where we will use analysis of the simulation state to predict an optimal routing solution.

Simulation-based Evaluation: To evaluate the performance of our proposed constrained route planning solutions, we will first compare the performance of our solution with a representative among existing state-of-the-art route planning solutions. Toward this end, we will follow a randomized process to simulate an ensemble of runs and compute the ensemble average as well standard deviations of the data points to ensure statistical reliability of the results. In each run of an experiment, we will measure and compare the network utilization as well as the constraint satisfaction percentage. Second, we will perform extensive evaluation of our proposed solutions in both data and parameter space, studying their performance as the data characteristics (e.g., congestion levels, road network structure/topology, source and destination distribution, etc.) and system parameters (e.g., solutions' parameters) change.

Dissemination: Dissemination of results from this project will target both academic and practitioner audiences. To reach academic audiences, we will produce conference presentations and peer-reviewed conference and journal papers to share findings of this project. Yet, even the best transportation research is of little value until that knowledge is effectively shared with a broader audience. Accordingly, we will make sure that the results are adapted for practitioner audiences, particularly via popular press articles. Specifically, to encourage technology transfer, we will present a research seminar via the Transportation Learning Network.

Expected Outcomes

The expected outcomes of this work include:

1. Three constrained system-optimal route planning solutions for fleet route planning, ridesourcing and ridesharing;
2. A simulation testbed for comparative evaluation of the proposed constrained route planning solutions versus existing state-of-the-art solutions;
3. Manuscripts for presentation/publication at TRB and other peer-reviewed journals; and
4. Presentations to academic, practice, and policy audiences.

In addition, our proposed constrained route planning solutions can possibly be implemented as mobile and/or desktop applications and offered to industry partners as well as the general public for their daily use, potentially resulting in significant improvement in utilization of the transportation networks at the regional and national level.

Relevance to Strategic Goals

The proposed research is aligned with the following two USDOT strategic goals (among other goals): Environmental Sustainability and Economic Competiveness. As mentioned before, fleet route planning, ridesourcing, and ridesharing are all among popular transportation scenarios with major impact on emission and energy footprint of transportation. Introducing efficient constrained system-optimal route planning solutions will significantly improve these footprints, and in turn, sustainability of the environment as well as economic competitiveness of the nation, respectively.

Educational Benefits

The students involved in this project (one PhD student and one MS student) will be trained in conducting research related to the field of transportation. These students will gain valuable research experience and have the opportunity to author publications and presentations emanating from this work.

This study will be integrated into Dr. Banaei-Kashani's graduate courses, namely, "CSCI Big Data Mining and Analytics" and "CSCI Big Data Systems" through a case study approach that will present research materials to the students and be incorporated into student term projects. The data collected for this project will also be made available to students for use in term projects and/or master's/PhD reports. As a result, this project will influence students from a variety of disciplines that comprise our future transportation professionals.

Technology Transfer

As mentioned before, the results of this study will be presented in relevant courses offered by the PI (e.g., CSCI Big Data Mining and Analytics and CSCI Big Data Systems), and disseminated through research publications and presentations. Moreover, we will present seminars in transportation practitioners' groups, such as the Transportation Learning Network, to communicate our results to practitioners in addition to researchers. Finally, the PI will also leverage his existing connections with relevant industry partners (e.g., FedEx, Uber and Lyft) as well as federal and state agencies (CDOT and NREL) to explore technology transfer and policy impact opportunities based on the results of this study.

Work Plan

The proposed scope of work is scheduled for a one-year timeframe, beginning with notice to proceed from the Mountain-Plains Consortium. Major project steps were described in previous sections. Here, we list these steps and present the timeline to implement the steps (NB: "S_i" is referring to the student who will be involved in the task, where "S_1" is a PhD student and "S_2" is an MS student; the PI will be involved with all tasks throughout the project period):

Task	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**
Design Constrained System-Optimal Route Planning Solution for ***Fleet Route Planning***	S_1	S_1										
Collection and Generation of Data for ***Fleet Route Planning***	S_2											
Extending Simulation Testbed for Evaluation of ***Fleet Route Planning***		S_2										
Executing Comparative Evaluation for ***Fleet Route Planning***			$S_{1\ \&2}$									
Design Constrained System-Optimal Route Planning Solution for ***Ridesourcing***				S_1	S_1							

Collection and Generation of Data for ***Ridesourcing***				S_2								
Extending Simulation Testbed for Evaluation of ***Ridesourcing***					S_2							
Executing Comparative Evaluation for ***Ridesourcing***						$S_{1\&2}$						
Design Constrained System-Optimal Route Planning Solution for ***Ridesharing***							S_1	S_1				
Collection and Generation of Data for ***Ridesharing***							S_2					
Extending Simulation Testbed for Evaluation of ***Ridesharing***								S_2				
Executing Comparative Evaluation for ***Ridesharing***									$S_{1\&2}$			
Incorporate lessons into graduate courses												
Dissemination / Technology Transfer												

Project Cost

Total Project Costs:	$99,966
MPC Funds Requested:	$49,974
Matching Funds:	$49,992
Source of Matching Funds:	Faculty Salary

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