Project Title:
Route Planning for Enhanced Transportation Network Utilization: A System Optimization Approach for Route Planning in Advanced Traveler Information Systems

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Research Needs:
Motivation: In 1991, the U.S. Department of Transportation (USDOT) initiated a new program to address the needs of the emerging field of Intelligent Transportation Systems (ITS). In this program, computing the “optimal” route (or path) for a traveler to commute from a designated source to a destination in a transportation network\(^1\) was identified as one of the main requirements of any Advanced Traveler Information System (ATIS). Subsequently, numerous route planning solutions were introduced by the research community and adopted by industry products (e.g., vehicle navigation devices, and online map services such as Google Maps\(^\circledR\)) 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,

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\(^{1}\) In this proposal, we mainly focus on route planning on road networks, and hence, we use “transportation network” and “road network” interchangeably.
overall travel quality, overall safety, and overall environmental sustainability. Our proposal addresses this misalignment by introducing an alternative approach to route planning where optimality of the routes is defined based on their impact on overall utilization of the transportation network.

Below first we will review the literature on routing planning. Thereafter, we elaborate on our proposed approach.

Related Work: A comprehensive survey of solutions for route planning in transportation networks is provided by Delling et al. [1] and more recently by Bast et al. [2]. In this section, we will briefly review various categories of existing solutions:

- **Basic Techniques:** The standard solution to the one-to-all shortest path problem is Dijkstra’s algorithm [3]. Numerous extensions of the Dijkstra’s algorithm are proposed [4,5,6,7,8,9,10,11,12] that marginally improve the asymptotic complexity of this algorithm from \( O (|V| + |A|) \log |V| ) \) to the best case of \( O (|A| + |V| \log \min(|V|, C)) \), where \( C \) is maximum edge cost. In practice, one can reduce the search space using bidirectional search [13], which simultaneously runs a forward search from source \( s \) and a backward search from destination \( t \). The algorithm may stop as soon as the intersection of their search spaces provably contains a vertex \( x \) on the shortest path from \( s \) to \( t \). For road networks, bidirectional search visits roughly half as many vertices as the unidirectional approach. An alternative method for computing shortest paths is the Bellman-Ford algorithm [14, 15, 16]. Although it runs in \( O (|V||A|) \) time in the worst case, it is often much faster, making it competitive with Dijkstra’s algorithm in some scenarios.

- **Goal-Directed Techniques:** Dijkstra’s algorithm scans all vertices with distances smaller than \( \text{dist}(s,t) \). Goal-directed techniques, in contrast, aim to “guide” the search toward the target by avoiding the scans of vertices that are not in the direction of \( t \); hence, improving the search performance by avoiding redundant traversal of the network. They either exploit the (geometric) embedding of the road network or properties of the graph itself, such as the structure of shortest path trees toward (compact) regions of the graph. Classic examples of goal-directed techniques include A* search and its [17, 18, 19, 20, 21, 22, 23, 24, 25], Geometric Containers [26, 27, 28, 29], Arc Flags [30, 31, 32, 33, 34], Precomputed Cluster Distances [35], and Compressed Path Databases [36, 37, 38].

- **Separator-Based Techniques:** Planar graphs have small (and efficiently-computable) small separators [39]. Although road networks are not completely planar (think of tunnels or overpasses) they have been observed to have small separators as well [40, 41, 42]. This fact is exploited by the so-called separator-based techniques for more effective route planning using a divide and conquer approach (separators partition the large network, practically reducing the large search problem to many small search problems that can be answered efficiently). Examples of separator-based techniques include Vector Separators [43, 44, 45, 46, 47, 48, 49], and Arc Separators [50, 51, 52, 40, 53].

- **Hierarchical Techniques:** Hierarchical methods aim to exploit the inherent hierarchy of road networks. Sufficiently long shortest paths eventually converge to a small arterial network of important roads, such as highways. Intuitively, once the query algorithm is far from the source and destination, it suffices to only scan vertices of this subnetwork. In fact, using input-defined road categories in this way is a popular heuristic [54, 55], though there is no guarantee that it will find exact shortest paths. Fu et al. [56] give an overview of early approaches using this technique. Example of extended solutions that
rely on hierarchical search idea include Contraction Hierarchies [57, 58, 59, 60, 61, 62, 63, 64, 53], and Reach [65, 66].

- **Bounded-Hop Techniques**: The idea behind bounded-hop techniques is to precompute distances between pairs of vertices, implicitly adding “virtual shortcuts” to the graph. Queries can then return the length of a virtual path with very few hops. Furthermore, they use only the precomputed distances between pairs of vertices, and not the input graph. A naive approach is to use single-hop paths, i.e., precompute the distances among all pairs of vertices \( u, v \) in the network. A single table lookup then suffices to retrieve the shortest distance. While the recent PHAST algorithm [67] has made precomputing all-pairs shortest paths feasible, storing all \((|V|^2)\) distances is prohibitive already for medium-sized road networks. Considering paths with slightly more hops (two or three) leads to algorithms with much more reasonable trade-offs such as Labeling Algorithms [68, 69, 70, 71, 72, 73, 74], Transit Node Routing [63, 75, 76, 77, 78, 57, 79], and Pruned Highway Labeling [80, 73, 81].

Moreover, since the individual techniques described so far exploit different graph properties, they can often be combined for additional speedups [82, 26, 83, 84, 85, 86, 61, 87, 33, 34]. Finally, many of the techniques considered so far can be adapted to compute batched shortest paths (such as distance tables) [88, 89, 90, 91, 92], to apply to more realistic scenarios (such as dynamic networks, where the cost of traversing each edge is variable, e.g., given the current road segment congestion) [93, 57, 62, 27, 94, 24, 95, 52, 96, 85, 97, 98, 99, 33, 100], or to deal with multiple objective functions with so-called multi-criteria path planning [101, 102, 103, 104, 105, 106].

As mentioned before, while route planning is well-explored by the research community, all of the aforementioned solutions are designed for route optimization for individual travelers rather than for the overall utilization of the transportation network.

**Proposed Work:**

We propose an alternative approach to route planning where optimality of the routes is primarily defined based on their impact on overall utilization of the transportation network rather than best interests of individual travelers. With this approach, the optimization criteria directly capture the transportation network/system interests, and therefore, route planning becomes a system optimization problem with which we seek a set of routes for the current travelers such that the overall utilization of the transportation network/system in terms of one or more utility functions (e.g., throughput-of/mobility-through of the transportation network, quality of transportation through the transportation network, etc.) is optimal. With such an approach, while we primarily optimize routes for network utilization, when possible and as a secondary objective we can still seek routes that are near-optimal (if not optimal) for individual travelers. Accordingly, with this proposal we will introduce a multi-criteria route planning solution with one or more network utilization criteria as primary optimization objective(s), and one or more measure(s) of best traveler interests as secondary objective(s).

We are motivated by the realistic scenario in which our proposed route planning solution is implemented as a mobile and/or desktop application (perhaps sponsored by regional USDOT agencies, and/or city and state partners which are interested in such “smart-cities” capabilities) and offered to general public for their daily use. While such an application will not necessarily provide the optimal (but perhaps near-optimal) route for each individual traveler, the public can
be incentivized to use this application (instead of the existing commercial route planning applications that merely focus on traveler interests) by offering breaks in fees/taxes that can be well justified by the improved network utilization.

Research Objectives:

With this proposal, we will:

1. Introduce a transportation network utility function that captures utilization of the network based on throughput-of/mobility-through of the transportation network (other network utilization criteria such as overall travel quality, safety, environmental impact, etc., can be studied as part of future work);
2. Design a multi-criteria route planning solution that uses the introduced utility function as the primary criterion and an exemplary traveler interest (e.g., fastest route) as the secondary criterion to generate optimal routes for travelers in a transportation network;
3. Develop a data-driven simulation testbed (based on realistic road network and traffic data) to evaluate the designed route planning solution and compare its performance versus state-of-the-art route planning solutions;
4. Advance knowledge by carrying out comparative analyses to answer our research questions;
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.

Research Methods:

To answer the research questions above, we will carry out a study that includes the following steps: (1) introduction of a new utility function to measure performance of transportation networks; (2) development of a multi-criteria route planning solution that considers network utilization as the primary optimization criterion; (3) data collection and generation for simulation-based evaluation; (4) development of the simulation testbed; and (5) execution of comparative evaluation to assess performance of the proposed solution versus state-of-the-art route planning solutions; and (6) dissemination. Below, we will review our proposed methodology in each case, where applicable.

Transportation Network Utility Function: Numerous studies are conducted in the past to measure performance and utilization of transportation networks (e.g., [107-113]). However, the existing measures for mobility often are spatiotemporal aggregate measures and fail to capture impact of route planning at the individual route level. While we will learn from existing literature, we need to introduce a new measure that allows assessment of the network mobility based on real-time data collected from the entire network as each new route is planned and scheduled.

Multi-Criteria Route Planning Solution: To develop a multi-criteria route planning solution that considers network utilization as the primary criterion and individual travelers’ interests as secondary criteria for optimization, we first focus on developing a (single-criterion) route planning solution that merely considers network utilization for route optimization. As mentioned in our literature review above, to the best of our knowledge such a solution has no precedent. To develop such a solution, while we can still learn from the past literature on optimal route planning (including our own work [114,115]), our main new challenge is that in this case
optimization must be performed based on 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 can simply rely on a local measures of performance (e.g., fastest route). Using a holistic measure for optimization is complicated as its real-time computation and application based on massive data poses a Big Data challenge. We intend to address this challenge by introducing a relevant instance of a summary data structure, dubbed sketch [116]. Such data structures can compute and maintain a small data summary based on the massive data collected from the network (therefore, efficient to compute and apply), while accurately estimating the holistic utility function.

Once we develop our single-criterion route planning solution for network utilization optimization, we will build on existing multi-criteria route planning [101, 102, 103, 104, 105, 106] to account for best interests of the travelers as secondary criteria (in addition to the network utilization) and develop our multi-criteria route planning solution.

Data Collection and Generation: To enable our simulation-based evaluation of the proposed route planning solution, we need both (road) network data as well as traffic data. We will obtain real road network data from TIGER dataset [117]. For traffic data, we will use an existing traffic data generator (e.g., MNTG [118]) 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.

Simulation Testbed: To develop our simulation testbed, first we will study two existing popular simulators, namely, BerlinMOD [119] and Thomas-Brinkhoff [120], to determine their applicability as the basic framework/platform to be extended for development of our own simulation testbed. If we find neither of these simulators sufficiently usable (e.g., whether they scale), we will develop our simulator from scratch, focusing on satisfying the evaluation requirements rather than developing a generic traffic simulation testbed. Toward this end, one of the main constraints is to make sure the simulation testbed is scalable; to address this challenge we will build on our past experience and use the existing facilities at our research laboratory (namely, Big Data Management and Mining Laboratory) to develop a testbed on a parallel processing platforms, including multi-core and/or many-core (e.g., GPU) platforms.

Simulation-based Evaluation: To evaluate the performance of our proposed route planning solution, we will first compare the performance of our solution with a representative among existing state-of-the-art route planning solutions, namely, Reach [65], which is also being used in practice in many existing ATISs. Toward this end, we will follow a randomized process to simulate an ensemble of scenarios and compute the ensemble average as well standard deviations of the data points to ensure statistical reliability of the results. In particular, for both solutions we will measure and compare network utilization as well as optimality of each route from the
traveler perspective. Second, we will perform extensive evaluation of our proposed solution in both data and parameter space, studying its performance as the data characteristics (e.g., congestion levels, road network structure/topology, source and destination distribution, etc.) and system parameters (e.g., solution 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. In particular, 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. A utility function to measure mobility/throughput in transportation networks at the route level
2. A multi-criteria route planning solution that considers network utilization as the primary criterion and best interests of individual travelers as the secondary criteria
3. A simulation testbed for comparative evaluation of the proposed route planning solution versus existing state-of-the-art solutions
4. Manuscripts for presentation/publication at TRB and other peer-reviewed journals; and
5. Presentations to academic, practice, and policy audiences.

In addition, as we mentioned before, in the future our proposed route planning solution can be implemented as a mobile and/or desktop application and offered to 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:**
This study primarily falls under the heading of Economic Competiveness. However, by merely introducing other utility functions for transportation networks, such as overall safety, overall travel quality, and overall environmental impact, this work will be readily applicable to other strategic goals, namely, safety, livable communities, and environmental sustainability, respectively.

**Educational Benefits:**
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, “Data Mining Techniques and Analytics”, “Database Systems”, and “Advanced Database 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.

**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 include
the following:

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**Project Cost**
Total Project Cost: $99,015.50
MPC Funds Requested: $49,507.50
Matching Funds: $49,508

**TRB Keywords:**
ITS; Planning; Routing; Performance Measurement; Mobility

**References:**
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