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Routing in Very Large Multi-Modal Time Dependent Networks: Theory and Practice

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In many path finding problems arising in diverse areas, such as transportation science [8], web search [4], database queries [1], [28], [42] and VLSI design certain patterns of edge/vertex labels in the labeled graph being traversed are allowed/preferred, while others are disallowed. Thus, the feasibility of a path is determined by (i) its length (or cost) under well known measures on graphs such as distance, and (ii) its associated label. In such a setting, many practical problems can be equivalently cast as multi-constrained shortest/simple path problems. An illustrative example is the problem of finding a fastest path in time dependent networks that have piecewise linear link traversal functions with the additional constraint that the label of the path belongs to a user specified regular grammar.

In this talk, I will discuss the modeling power, robustness to modifications (extensibility) and computational complexity of solving such multi-constrained routing problems. Our primary motivation for studying such problems was the TRANSIMS project for transportation analysis and simulation [9]. Nevertheless, many of the solutions are not TRANSIMS-specific, but applicable to a number of other realistic transportation problems.

TRANSIMS is a multi-year project at the Los Alamos National Laboratory and is sponsored by the Department of Transportation and by the Environmental Protection Agency. The purpose of TRANSIMS is to develop new models and methods for studying transportation planning questions. A prototypical question considered in this context would be to study the economic and social impact of building a new shopping complex in a large metropolitan area. We refer the reader to [10], [13], [9] and the website `http://transims.tsasa.lanl.gov` to obtain extensive details about the TRANSIMS project. TRANSIMS conceptually decomposes the transportation planning task into three time scales. The largest time-scale consists of land use models and demographic distribution as a characterization of travelers. In this phase, virtual individuals making up a household are created in a way so as to match the census demographic data. An intermediate time-scale consists of activity generation and route planning. First, available survey data is to used to create *activities* for each traveler. Activity information typically consists of requests that travelers be at a certain location at a specified time and also includes information on travel modes available to the traveler. Next, the route planning phase assigns routes and trip-chains to satisfy the activity requests. The route planning module is the focus of this paper. Finally, a very short time-scale is associated with the actual execution of trip plans in the network. This is done by a simulation that uses a cellular automata representation of vehicles in a very detailed representation of the urban transportation network.

The basic purpose of the route planner is to use the activity information (generated earlier from demographic data) about a traveler to determine optimal and consistent mode choices and travel routes for each individual traveler. The routes need to be computed for a large number of travelers. For example, in the Portland case study 5–10 million trips are planned. In order to remove the forward causality artificially introduced by this design, and with the goal of bringing the system to a “relaxed” state, TRANSIMS has a feedback mechanism: the link delays observed in the micro-simulation are used by the route planner to re-plan a fraction of the travelers. Clearly, this mechanism requires a high computational throughput from the planner. The high level of detail in planning and the efficiency demand are both important design goals; methods to achieve reasonable performance are well known if only one of the goals needs to be satisfied.

In view of the above design requirements, I will discuss a unified modeling framework and associated efficient algorithms for constrained shortest paths in multi-modal and time-dependent networks. This framework and the associated algorithms are at the core of the route planner. The framework offers a number of advantages including, (1) translation of “real world” questions into mathematically well-defined optimization problems, (2) guidance in the development of algorithms for these problems, and (3) a *single efficient algorithm* for a host of seemingly different optimization problems in transportation science. In addition, the results, modeling applications and the experimental data obtained suggests that the formalism provides a balanced solution to the conflicting goals of (i) modeling power, (ii) extensibility and (iii) computational cost. As illustrations of the practical utility, we show how to use this framework and the associated algorithm to solve extremely large realistic transportation problems. From a pragmatic point of view, a generic algorithm simplifies the implementation of and experimentation with alternative models. The formalism is best described in three steps.

First, we consider models and algorithms for shortest paths with discrete choice constraints. These include travel modes, destination choice, roadway type, etc. In general many of these choices cannot be modeled adequately by edge-weights, but edge- or vertex-labels are more appropriate. Motivated by this, we represent the transportation network by a (possibly time-dependent) *weighted*, (vertex- and/or edge)-*labeled* graph. The labels denote modal or other discrete attributes of the edge (vertex) and are drawn from a finite set. We use regular expressions over the label set to describe feasible paths, explain how to solve these problems efficiently and show how this model encompasses a wide variety of discrete-choice transportation problems. For more details, see [12].

Second, we discuss finding (optimal) paths in time-dependent networks. This is an important problem in transportation science [15], [16], [44], [45], [46]. We propose monotonic piecewise-linear link traversal functions to model time-dependence. We argue that this class is (1) adequate for modeling time-dependent edge lengths in rapidly changing conditions on roadways, (2) flexible enough to describe more complicated scenarios such as scheduled transit and time-window constraints and (3) allows computationally efficient algorithms. For example, a prototypical question consists in finding the shortest route that takes into account the bus and train schedules. We solve this problem efficiently in our framework. The ideas we present here are built on a well-established literature on time-dependent shortest-path problems (for a survey see Orda and Rom [31]).

Third, we show how to combine the two models (labels and time-dependence) and the proposed algorithms to capture a variety of important problems including time-windows, trip chaining, etc. These results further demonstrate the robustness of our models and algorithms. To the best of our knowledge, only heuristic methods have been used so far to solve such problems. Finally, we discuss how the formalism can be extended to allow non-negative edge/vertex weights that capture situations such as tolls, etc. We briefly discuss an extension of the algorithm to handle this case. See [6] for details.

As discussed earlier, the algorithms described above have been implemented as part of the TRANSIMS project. This allowed testing our methods on real transportation networks. In order to anchor research in realistic problems, TRANSIMS uses example cases called *Case studies* (see [10], [13] for details). Two case studies have been designed—the first one, concluded in May 1997, focused on the Dallas/Fort-Worth (DFW) metropolitan area. It was done in conjunction with a municipal planning organization (MPO) (the North Central Texas Council of Governments, NCTCOG). The second case study is currently underway and focuses on Portland, Oregon. While the goal of the DFW case study was mainly validating uni-modal traffic simulation, the Portland case study will attempt to validate our models and algorithms for multi-modal time-dependent networks. These networks consist of over half a million nodes and over three million edges. In order to experimentally analyze the behavior of the algorithms in realistic settings we employ simple but well known statistical techniques (e.g. ANOVA). Such formal statistical techniques and associated experimental designs provide an excellent tool to carry out empirical analysis of algorithms. See [7], [11] for other examples. A more detailed experimental study can be found in [25], [6]. See [36], [37] for examples of recent work aimed at design and implementation of shortest path algorithms for very large and realistic transportation networks.

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