Value of Information for Optimal Adaptive Routing in Stochastic Time-Dependent Traffic Networks: Algorithms and Computational Tools

Principal Investigator
Song Gao, Ph.D.
Assistant Professor of Civil and Environmental Engineering
University of Massachusetts
214C Marston Hall
130 Natural Resources Road
Amherst, MA 01003
Tel: 413-545-2688
Fax: 413-545-9569
Email: songgao@ecs.umass.edu

Abstract:

The objective of the project is to develop algorithms and computer implementations to study a class of optimal adaptive routing problems in stochastic time-dependent traffic networks where a wide variety of traveler information situations can be modeled and the value of information can be compared. The project is motivated by two observations of the traffic system: 1) the system is inherently uncertain with random disturbances such as incidents, bad weather, work zones and so forth; and 2) traveler information is or will be available so that travelers could make travel decisions adaptive to the random disturbances to reduce negative effects of uncertainty. The project will contribute to the state of the art by solving a class of fundamental network optimization problems; it will also provide algorithms and computer software for assessing effects of various forms of Advanced Traveler Information Systems (ATIS) in terms of reducing expected travel time and increasing travel time reliability.

1. Statement of Project Objectives

We propose to develop efficient algorithms and computer implementations for a class of optimal adaptive routing problems in stochastic time-dependent traffic networks where a wide variety of traveler information situations can be modeled and the value of information can be compared. The project is motivated by two observations of the traffic system. First, traffic networks are inherently uncertain with random disturbances which creates significant congestion, as described in the 2003 Urban Mobility Report by the Texas Institute of Transportation (Schrank and Lomax, 2003, [p. V]): “Crashes, vehicle breakdown, weather, special events, construction and maintenance activities greatly affect the reliability of transportation systems; these delays account for about 50 percent of all delay on the roads.” A stochastic time-dependent network is required to capture such uncertainties in a dynamic context. Secondly, the development of modern travel information systems is based on the premise that better-informed travelers can make route choices that increase welfare and collectively reduce the system-wide congestion. However, rigorous studies are required to assess this assumption. There are various mechanisms for providing online information differing in the spatial and temporal availability, the quality, and the format of information provided, e.g. variables message signs (VMS), websites, radio, traveler information call centers, in-vehicle communication systems connected to traffic management centers, and so forth. It follows that in formulating ATIS related research problems, information should be an explicit part so that traditional simplified assumptions such as full or no information can be avoided.

Travelers' routing decisions in a stochastic network with online information are conceivably different from those in a deterministic network. It is generally believed that adaptive routing will save travel time and enhance travel time reliability. For example, in a network with random incidents, if one does not adapt to an incident scenario, he/she could be stuck in the incident link for a very long time. However, if adequate online information is available about the incident and the traveler adapts to it by taking an alternative route, he/she can save travel time compared to the non-adaptive case. The adaptiveness also ensures that the travel time is not prohibitively high in incident scenarios, and thus provides a more reliable travel time.

The proposed research will build upon a general framework of optimal adaptive routing problems in stochastic time-dependent networks developed by the principle investigator (Gao and Chabini, 2006). The general framework allows for specialization of problem variants according to assumptions on information access. Variants with perfect online information and arrival-time-only information have been studied extensively (Gao, 2005), and this research will focus on information situations pertinent to the current technology development that are generally limited spatially and/or temporally. More specifically, we aim at achieving the following:

- Study theoretically the relationships between expected travel times obtained from optimal routing in different traveler information situations. Prove or give counter examples that information with larger spatial and/or temporal dimension(s) leads to no-worse expected travel time, i.e. the value of information on additional links and/or time periods is always non-negative;

- Design exact algorithms to solve the optimal adaptive routing problems with the following realistic information situations: information provided by VMS; information with a time lag; information on given critical routes broadcasted by radio;
- Study the theoretical correctness and complexity of the exact algorithms, and decide on the necessity to design approximate algorithms. Design approximate algorithms, if needed, that trade off optimality of solutions for computational efficiency; and
- Develop a library of efficient computer implementations of the proposed algorithms, and study computationally the value of information in various information situations proposed in previous and current projects, in both hypothetical and real networks.

2. Research Contribution

This research will contribute to the state of the knowledge in the following aspects:

- The first rigorous study of the value of online information for optimal adaptive routing as a function of the scope of the information in general stochastic time-dependent networks, both theoretically and computationally. The result will provide foundation for the evaluation of traveler information systems.
- The first formulation, algorithm design and computer implementation of adaptive routing problems in stochastic time-dependent networks explicitly considering a number of realistic traveler information situations. Note that link-wise and time-wise stochastic dependencies among link travel times are also modeled, and thus the problems studied are among the most realistic formulations of routing problem with real-time information.

The proposed research not only holds the potential to advance the state of knowledge but also the state of the practice. Research results in the form of algorithms, computer implementations and software libraries are of interest to organizations from the information technology and transportation systems industries, especially those involved in traveler information systems, such as traffic management centers, traffic information centers, commercial global positioning system (GPS) providers, wireless telephone service providers, and so forth.

3. Technical Approach or Methodology

3.1. Optimal Routing Policy Problems in Stochastic Time-Dependent Networks

We have established (Gao and Chabini, 2006) a framework to provide a unified view of optimal routing policy problems in a stochastic time-dependent network. In the rest of the proposal, we will use “ORP problems” to denote the problems we are to study. Otherwise indicated, an ORP problem is a problem in a stochastic time-dependent network (as opposed to a static network). We are able to see the connections among various variants in the literature with the aid of the framework, and generate new variants that are required by specific applications. The generic optimality conditions can provide a general way of designing solution algorithms for variants of the problem.

Let $G = (N, A, T, P)$ be a stochastic time-dependent (STD) network. N is the set of nodes and A is the set of links. Let m be the number of links: $m = |A|$. T is the set of time periods $\{0, 1, \ldots, K\text{-}1\}$. A "support point" is defined as a distinct value (vector) that a discrete random variable (vector) can take. Thus a probability mass function (PMF) of a random variable (vector) is a combination of support points and the associated probabilities. Throughout this paper, a symbol with a ~ over it is a random variable, while the same symbol without the ~ is one specific support of the random variable. Travel time on each link (j, k) at each time period t is a random variable $\tilde{C}_{jk,t}$ with finite number of discrete, positive and integral support points. Beyond time period K-1 travel times are static and deterministic, i.e. travel times on link (j, k) at any time $t \geq K\text{-}1$ is equal to $C_{jk,K-1}$. P is the probabilistic description of link travel times. Different descriptions exist because of different assumptions about network probabilistic distributions. The most general one is in the form of a joint probability distribution of all link travel time random variables: $P = \{v_1, v_2, \ldots, v_R\}$, where v_i is a vector of dimension $K \times m$, $i = 1, 2, \ldots, R$, and R is the number of support points. The r-th support point has a probability p_r, and $\sum_{r=1}^{R} p_r = 1$. $C^r_{jk,t}$ is the travel time of arc (j, k) at time t in the r-th support point.

Assume the traveler knows *a priori* the probabilistic description P and make decisions at nodes. The decision is what node k to take next at each node, based on the current *state* $x = \{j, t, I\}$, where j is the *current-node*, t is the *current-time*, and I is the *current-information*. Current-information I is defined as a set of realized link travel times at current-node j and current-time t that are useful in making inferences about future link travel times. Note that current-information is one component of a state and refers to link travel time realizations based on which the current decision is made, while a reference to "information" alone is in a general sense. A *routing policy* $\mu(x)$ is defined as a mapping from all possible states to decisions (next nodes).

Assume we want to optimize the travel in the STD network. Since link travel times are random variables, there exist multiple criteria for an optimal travel choice. The expected travel time is used in this research, as generally it is the primary criterion in routing choices. Other criteria, such as travel time variance and expected travel time schedule delay, and a combination of some of the criteria, have been explored in other research (Gao, 2005).

The current-information depends on two factors: *network stochastic dependency* defining the stochastic dependency of link travel time random variables, and *information access* defining which link travel time realizations are available to the travelers at any given time and given node. The taxonomy of the ORP problem is therefore along these two dimensions.

Information Network	Perfect Online	Partial Online	Arrival Time Only
No Time-Wise and Link-Wise Dependency			Hall (1987), Miller-Hooks and Mahmassani (2000), Chabini (2000), Pretolani (2000), Bander and White (2002), Yang and Miller-Hooks (2004), Opasanon and Miller-Hooks (2006)
Complete Dependency	Gao and Chabini (2002, 2006)	Gao (Ongoing)	
Partial Dependency		Boyles (2006)	

TABLE 1: Taxonomy of the ORP Problem in Stochastic Time-Dependent Networks

Network stochastic dependency is characterized by link-wise and time-wise stochastic dependencies of link travel times. At one extreme, all the link travel time random variables are independent, both link-wise and time-wise. At the other extreme, all the link travel time random variables are completely dependent. There are numerous cases in between these two extremes, and we denote them as partial stochastic dependency.

Information access has the following three categories: 1) perfect online information; 2) partial online information; 3) arrival time only. Travelers with *perfect online information* have knowledge of the realizations of all link travel times up to current time period. Travelers with *partial online information* only have knowledge of part of the link travel time realizations and the restrictions can be either temporal or spatial or both. Travelers with *arrival time only information* have no knowledge of any of the realizations and the only knowledge they have about the current state is the current-node and current-time. Table 1 gives a literature review on some representative studies of ORP problems based on a possible taxonomy along the two dimensions.

We propose to establish theoretical properties of the relationship among solutions of the optimal routing policy problems with different information access assumptions. Specifically we are interested in the following hypothesis: in a given stochastic time-dependent network *G*, for two current-information $\tilde{I}_1$ and $\tilde{I}_2$, if $I_1^r(j,t) \subseteq I_2^r(j,t), \forall j \in N, \forall t \in T, r = 1,\cdots,R$, then the solution of the ORP problem with $\tilde{I}_2$ cannot be worse than that with $\tilde{I}_1$. A more intuitive description is that more information leads to better decisions.

The hypothesis is derived from the observation on the relationship among solutions from perfect online information, arrival-time-only information, and simple paths. A simple path is a special routing policy where the same next node is taken regardless of the arrival time and information at the decision node, and an arrival-time-only routing policy is a special perfect-online-information routing policy where the same next node is taken regardless of the information. Therefore the solution to the minimum expected travel time path problem is a feasible solution to the minimum expected travel time routing policy problem with arrival-time-only information, which is a feasible solution to the minimum expected travel time routing policy problem with perfect online information. Since a feasible solution is no better than an optimal solution, we can conclude that the solution from perfect online information is at least as good as that from arrival-time-only, which itself is at least as good as that from a simple path. However, the generalization of the result is not straightforward. The key of the above arguments is that the optimal solution of one problem is a feasible solution of another. The same connection is not necessarily true for two general forms of current-information. We propose to either prove or give counter example to the hypothesis, and the result will provide theoretical foundation for the evaluation of traveler information systems.

3.2. Information Access Assumptions: Specialization of the General Problem

The power of the concept of routing policy lies on that fact that online information is embedded in a traveler's route choice alternatives and, thus, systematic methods can be designed independent of online information formats. The general definition of a routing policy allows for a wide variety of information accessibility situations, thus excluding the usually simplified assumptions such as either no information or full information. The various online information situations include, but are not limited to:

- perfect online information provided by in-vehicle communication systems connected to a traffic information center,
- partial online information provided by radio,
- VMS,
- vehicle-to-vehicle communication systems,
- telephone-based information centers, and
- personal observations.

Full information, perfect online information and arrival-time-only information have been studied in Gao (2005) and Gao and Chabini (2006). Travelers with *full information* have knowledge of the realizations of all link travel times before the trip. This is not a realistic situation, but it results in lower bounds for all other variants of the ORP problem, and thus can be used as a benchmark in the effectiveness analysis of solutions to other variants. The above variants are our first attempt to understand optimal routing policy problems, and prepare us with algorithmic and computational experience to tackle more realistic problem variants.

We propose to study three problems variants with realistic information situations: variable message signs, global information with time lag, and broadcasted information on critical links.

Variable message signs are among the most commonly utilized means to deliver traveler information nowadays, and therefore the study of an optimal routing policy problem with information provided by VMS is of both theoretical and practical importance. A VMS is usually fixed in location and thus only travelers passing it can obtain the information. It is also limited in the amount of information it can provide, due to the limitation of the display panel. Usually it simply tells traveler that an incident happened somewhere, and sometimes with estimated delay on an affected major route. The number and locations of VMS are also input to the problem.

A possible specialization of the VMS information access is described as follows. Assume VMS can only be placed at a node. This assumption is not restrictive, since a link can always be divided at the VMS location if it is placed in the middle of a link. A node without VMS is denoted as a regular node, while that with VMS is denoted as a VMS node. The current-information at a regular node can take two forms: 1) empty, if the traveler has not visited any VMS; 2) links covered by all VMS that the traveler has visited. The current-information at a VMS node contains links covered by previous VMS (if any) visited by the traveler and links covered by the current VMS. All link travel times are time-dependent, i.e. if the traveler passes VMS 1 at 8:00am and VMS 2 at 9:00am, then the current-information at VMS 2 contains links covered by VMS 1 at 8:00am and VMS 2 at 9:00am. Travel times of links covered by VMS 1 at 9:00am are no longer available to the traveler. We propose to start with the one-VMS problem which seems to be the easiest and then explore problems with multiple VMS where the possible combined visits to multiple VMS inevitably complicate the problem.

Traffic information is usually delivered with some time lag, for example, at 8:00am you might only learn link travel time realizations up to 7:45am. The ideal perfect online information variant assumes information is up to the current time, and therefore it is interesting to see how the time lag affects the expected travel time. Compared to the VMS problem, the information limitation in the time-lag situation is temporal rather than spatial.

Radio broadcast of traffic conditions on some critical links, usually major highways and arterials is another common form of information access. Usually these critical links are also among the most congested and stochastic. It is hypothesized that information on these links has the highest value. The availability of the information is assumed to be ubiquitous (radio signal is generally available at any node in the network). In another word, the information is not a function of location as in the VMS case. Therefore the radio broadcast problem is conceivably easier than the VMS problem.

We propose to 1) define vigorously and realistically the above three partial online information situations, including the composition of the dynamic links to be included in the current-information and the underlying probabilistic description of the network; 2) design algorithms to solve the problems and analyze their theoretical complexity; 3) design approximate algorithms, if needed, to enhance computational efficiency with reasonable suboptimal solutions.

3.3. Computational Studies

We propose to conduct computational tests of the optimal routing policy algorithms for the six information situations: 1) full information, 2) perfect online information, 3) arrival-time-only information, 4) VMS, 5) global information with time-lag, and 6) broadcast information on critical links. The objectives of the computational tests are:

- Study the average running time of an algorithm as a function of network size, which is a complement to the theoretical complexity analysis;
- Compare the expected travel time and variance of optimal routing policies with different information access assumptions and conduct sensitivity analysis of the value of information with respect to problem parameters, such as network size, link travel time correlation, number of VMS, the critical link sets covered by radio, and so forth.

We propose to conduct the tests on both hypothetical and real-life networks. The hypothetical network is easy to analyze and convenient to isolate factors that affect results, and therefore can provide useful insights into the problems. The real-life network, on the other hand, could be of practical importance. We propose to work with relevant agencies in the state, such as the Mass Highway, the Executive Office of Transportation, and the MBTA, or other research institutes to identify a suitable real life network to work with.

4. Anticipated Results

One of the primary contributions of this research project would be the design and computer implementation of new algorithms for adaptive optimal routing in stochastic time-dependent networks with a variety of real-time information situations. Tangible results would be in the form of computer software, which will be made available to USA companies in information technology and transportation systems industries. This project should be a significant advance in the methodological aspects of algorithms, computing and transportation systems operation. Another important result will be the theoretical and computational comparison of various real-time information systems, which would provide guidelines and knowledge base for transportation agencies to support a variety of decision makings in traveler information systems.

5. Technology Transfer

There would be several forms of technology transfer used to disseminate the results of this research. We will present the results of this research at various seminars at University of Massachusetts Amherst and at other Universities, and at national as well as international professional meetings such as the annual meetings of the Transportation Research Board, INFORMS and the IEEE Intelligent Transportation Society. At the end of this project, we will provide transportation researchers and practitioners with a comprehensive research report describing our research results. We will also publish our research results in research journal such as Transportation Science, Transportation

Research, Transportation Research Record, Journal of ASCE and so forth.

6. Principle Investigator and Other Staff

The Principal Investigator of this research program will be Professor Song Gao (see the CV on the next page). Other personnel include one transportation graduate-degree candidate at the University of Massachusetts Amherst (to be nominated).

University of Massachusetts Amherst

Song Gao

Assistant Professor of Civil and Environmental Engineering

EDUCATIONAL BACKGROUND

Ph.D. in Transportation, February 2005, Massachusetts Institute of Technology, Cambridge, MA

M.S. in Transportation, February 2002, Massachusetts Institute of Technology, Cambridge, MA

B.S. in Civil Engineering, July 1999, Tsinghua University, Beijing, China

PROFESSIONAL EXPERIENCE

Transportation Engineer, Caliper Corporation, Newton, MA, Dec 2004 – Aug 2007

Teaching and Research Assistant, Massachusetts Institute of Technology, Cambridge, MA, Sep 1999 – June 2004

SELECTED AWARDS

INFORMS Transportation Science and Logistics Dissertation Prize Competition, Honorable Mention (Second Place), 2005

MIT United Parcel Service (UPS) Doctoral Fellowship, 2001-2002

MIT Presidential Fellowship, 1999-2000

Mao Yi-sheng Engineering Education Fellowship, 1998 (Awarded annually to six best Civil Engineering college students in China)

SELECT RECENT PUBLICATIONS

Ben-Akiva, M. E., J. Bottom, S. Gao, H. Koutsopoulos and Y. Wen. Towards Disaggregate Dynamic Travel Forecasting Models. *Tsinghua Science and Technology*, 12(2):115-130, 2007.

Gao, S. and I. Chabini. Optimal Routing Policy Problems in Stochastic Time-Dependent Networks. *Transportation Research Part B*, 40(2):93-122, 2006.

Gao, S. Online Traveler Information in Stochastic Dynamic Networks. *Proceedings of the IEEE 9th International Conference on Intelligent Transportation Systems*, Toronto, Canada. Sep. 17-20, pp. 204-211, 2006.

Gao, S. Equilibrium Dynamic Traffic Assignment with Adaptive Routing Decisions. *Proceedings of the 85th Annual Meeting of Transportation Research Board CD-ROM*, Washington, DC, Jan. 22-26, 2006.

Gao, S. and I. Chabini. A Policy-Based Approach to Dynamic Traffic Assignment. *Proceedings of the 82nd Annual Meeting of Transportation Research Board CD-ROM*, Washington, DC, Jan. 12-16, 2003.

Gao, S. and I. Chabini. Best Routing Policy Problem in Stochastic Time-Dependent Networks. *Transportation Research Record 1783,* pp.188-196, 2002.

8. References

Boyles, S. D. (2006) Reliable Routing with Recourse in Stochastic, Time-Dependent Transportation Networks. Master's Thesis. The University of Texas, Austin, TX, USA.

Chabini, I. (2000) Minimum expected travel times in stochastic time-dependent networks revisited, working paper.

Gao, S. and Chabini, I. (2002) The best routing policy problem in stochastic time-dependent networks, *Transportation Research Record 1783*, pp. 188-196.

Gao, S. (2005) Optimal Adaptive Routing and Traffic Assignment in Stochastic Time-Dependent Networks. PhD Dissertation. MIT. Cambridge, MA, USA.

Gao, S. and Chabini, I. (2006) Optimal Routing Policy Problems in Stochastic Time-Dependent Networks, *Transportation Research Part B*, 40(2):93-122.

Hall, R. W. (1986) The fastest path through a network with random time-dependent travel times, *Transportation Science* 20(3):182-188.

Opasanon, S. and Miller-Hooks, E. D. (2006) Multicriteria Adaptive Paths in Stochastic, Time-Varying Networks, *European Journal of Operational Research*, 173:72-91.

Miller-Hooks, E. D. and Mahmassani H. S. (2000) Least expected time paths in stochastic, time-varying transportation networks, *Transportation Science* 34(2):198-215.

Pretolani, D. (2000) A directed hyperpath model for random time dependent shortest paths. *European Journal of Operational Research* 123:315–324.

Schrank, D. and Lomax, T. (2003) The 2003 annual urban mobility report. Technical report, Texas Transportation Institute (http://mobility.tamu.edu/).

Yang, B. and Miller-Hooks, E. (2004) Adaptive routing considering delays due to signal operations. *Transportation Research Part B* 38B:385–413.