A Combinatorial Auctions Framework for Real-Time Traffic Network Control with Advanced Information Systems

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1 Introduction

The primary functional capabilities of a dynamic traffic assignment (DTA) module for advanced traveler information systems (ATIS) operations are to predict the network state over time and to provide routing information to drivers consistent with some individual and/or system-wide objectives (Peeta and Yu, 2004). The traditionally proposed DTA models for the real-time operational control of large-scale vehicular traffic networks under information systems are behaviorally restrictive and limited in their ability to model driver response to information. This motivates the development of a DTA paradigm integrating traffic control/information provision decisions and realistic driver behavior representation. This paper seeks to propose a general framework to generate effective real-time information provision strategies with a more robust prediction of driver route choice behavior using a combinatorial auctions (CA) approach on an agent-based simulation (ABS) platform.

2 Driver behavior issues in the existing DTA models

From a deployment perspective, DTA models can be classified into iterative, reactive and hybrid types (for a detailed review, see Peeta and Ziliaskopoulos, 2001). Driver behavior is a fundamental factor and the key source of complexity in predicting the traffic network states unfolding over time for these models. The current DTA literature does not address driver behavior realistically and sufficiently. Only a few DTA models consider heterogeneity among drivers. Even these models are behaviorally restrictive, and assume that the driver behavior classes are pre-specified. This implies homogenous information availability and response behavior for drivers in the same user class. Further, they assume that the driver behavior class fractions in the ambient traffic stream are known deterministically *a priori*. Incorrect prediction of the traffic system based on these assumptions can result in negative impacts on the validity and effectiveness of the information supply strategy of system controllers and/or information service providers, and potentially deteriorates system performance. In the real-world, the natural mechanism for driver route choice, even under information provision, is based on the driver's innate behavioral tendencies, past experience, situational factors (such as time-of-day, weather conditions, and trip purpose), and the ambient traffic conditions encountered. This is true irrespective of whether drivers receive personalized, generic, or no information (Peeta and Yu, 2004). While information provision and content can be used as control variables to influence system performance (Peeta and Gedela, 2001), they cannot imply perfect compliance by the drivers to the supplied information, as is predominantly done in the DTA arena. Even studies that view compliance as a variable are restrictive because they still assume rigid behavioral classes. Further, they mostly model compliance through compliance rates by assuming that these rates represent the fraction of drivers that fully comply or do not comply with the provided route. This approach has limitations from a real-world perspective. First, not all drivers with access to information receive personalized routes. Second, even when personalized routes are recommended, compliance is not an "all-or-nothing" variable in terms of how the information is used. People may use the information to partly modify the existing route based on their behavioral tendencies and past experience.

Peeta and Yu (2004) propose a behavior-based consistency-seeking (BBCS) modeling approach to bridge the functional gaps between route choice models and DTA models vis-à-vis predicting the time-dependent network traffic flow patterns. The approach consistently addresses day-to-day learning and within-day dynamics using a single hybrid probabilistic-possibilistic behavioral model through intuitive *if-then* rules that are based on the findings of past studies in the literature. The approach avoids rigid assumptions on driver behavioral tendencies and *a priori* knowledge of driver behavior class fractions. It enables the classification of information characteristics and the modeling of information effects more consistently with the real-world. The BBCS models can serve as alternatives to DTA models to develop deployable information supply strategies to control system performance, thus ensure greater realism in this context compared to dynamic traffic assignment models. However, innovative in modeling richer driver information response behavior, this approach still uses the iterative approach inherited from traditional DTA models for the information-based control strategy generation procedure. From the traffic controller and/or information service provider perspective, providing personalized or class-specified information based on better understanding of driver information response tendencies and ambient traffic conditions could generate a more effective control paradigm. Such paradigm aims to answer questions such as “whom to provide information to” and “what information to provide” based on accurate prediction of underlying driver decision characteristics.

The explicit consideration of driver behavior results in extra dimension of complexity in predicting traffic states, and this is further complicated by the need to adequately capture traffic flow dynamics that represent the network-level temporal and spatial interactions of driver route choice decisions. The third dimension of complexity stems from the bi-level structure of the decision-making procedure in both traffic controller/information service provider level and individual drivers level. The common DTA objectives, inherited from static traffic assignment concepts, are UE and SO with single-level optimization structure. In the DTA operational context, using UE as a behavioral paradigm, or UE and SO as information supply strategies with partial or perfect compliance, are inherently restrictive from a behavioral standpoint. This is because they exclude from explicit consideration situational factors and driver learning (which is based on past experience, personal characteristics, and latent tendencies towards information provision), both of which can significantly affect driver route choice decisions on a specific day. This implies the need for seamless and consistent integration of information-based control strategy and richer driver behavior representation. We propose a combinatorial auctions (de Vries and Vohra, 2003) framework to model the bi-level decision-making problem in this context, and an ABS platform to capture the traffic flow dynamics and network-level interactions of driver route choice decisions.

3 Combinatorial auctions framework

Combinatorial auctions have received significant attention from computer scientists, operations researchers and economists in recent years. In such auctions, bidders are allowed to bid on any combinations (also termed as sets or bundles) of heterogeneous objects that they are interested in. Since the objects in a set have complementary relations, the bidding price of the set is not the summation of bidding prices for all objects in the set. Static combinatorial auctions are typically first-price, sealed bid auctions. Bidders evaluate the private value of various sets based on public information and personal preference, and submit a set of bidding pricing for the sets interested. The auctioneer chooses the winning bids so as to get the optimal payment, meanwhile making sure that no sets/objects are assigned twice. In the Transportation arena, combinatorial auctions have been used in several contexts such as freight transportation service procurement (Caplice, 1996) and supply chain management (Walsh et al., 2000).

Both the auctioneer and bidders solve combinatorial problems. This is analog to the construct of a behavior-based traffic control (BBTC) problem. Therefore, we use the dynamic combinatorial auctions setting to formulate such problem. Let the traffic controller and/or information service provider represent the auctioneer in the auctions, and let the drivers be the bidders. Links of the traffic network can be thought of as objects in the auctions, and paths are the combinations of objects (links). During the auctions, auctioneer broadcasts object price (link travel cost) related information to bidders. Based on this information as well as personal behavior tendency, past experience, situational factors and the decisions of other bidders (ambient traffic conditions), a bidder selects one set among all interested sets (all paths connecting the original-destination (O-D) pair for this bidder), and submits a bid to the auctioneer indicating the interest of one set. All bids will be treated as winning bids and be accepted in each bound of bidding. The aggregation of all individual bidder decisions will decide the overall performance of the traffic network. The auctioneer collects the bids from all bidders, and measures the system performance using on-site sensing equipment. He/she then decides the information provision strategy for the next round of auction based on a system-level performance objective function.

Though similar in conceptual structure and computational hierarchy, the BBTC problem and a general static CA problem are different in several aspects: (i) the BBTC is a dynamic procedure instead of a sealed bid auction; (ii) in a general CA problem, the objective function for the auctioneer optimization problem is a linear combination of all winning bids, and the decision variable is the object assignment. In a BBTC problem, the objective function to the auctioneer is typically a non-linear function of bidding decisions. The value of such objective function is not easily measurable. Therefore, simulation-based approach is usually used for system performance measurement; (iii) in a general static CA problem, the decision on winners and winning bids are decided by the auctioneer. In the BBTC problem, each bidder only submit bid for one set of objects in each round, and all submitted bids are accepted by the auctioneer as winning bids. That is, the driver accomplish his/her travel whichever route is chosen; (iv) in BBTC setting, bidders only bid for certain sets that connect specific O-D pairs; in general CA, the potential sets of bidders can be much broader. Despite of these differences, the behavioral explanation and solution techniques for general CA problem can be adapted to solve the BBTC auctions.

While BBTC modeling can potentially reap huge benefits from the use of combinatorial auctions, several difficult problems emerge. It is well known that the bid valuation and construction problem for CA is very difficult and involves the computation of a number of NP-hard sub problems. Several recent studies have pointed out the computational difficulties of the bidders' valuation problem in these auctions (Parkes, 2000). In recent years, there has been a surge of interest in the design and use of combinational auctions across many applications (de Vries and Vohra, 2003). The winner determination problem, the problem of assigning winning and non-conflicting bids to bidders with maximal benefits have received the most attention in the research related to CA. It can be formulated as a variant of either the set covering problem or the set partitioning problem or the set packing problem depending on whether it is a forward auction (revenue maximization) or reverse auction (cost minimization) and depending upon auctioneer's constraints. In all cases these are NP-complete problems. Both exact and approximation algorithms have been studied in the past for the winner determination problem, mostly from a re-discovery of past algorithms for the set packing (covering, partitioning) problem. A detailed review of formulations and algorithms for the winner determination problem can be found in de Vries and Vohra (2003).

With the added dimension of complexity caused by explicit consideration of driver behavior, non-traditional numerical solution methods are needed for the BBNC problem. An agent-based simulation approach is introduced in this paper. Auctioneer and bidders are formulated as non-cooperative self-interested rule-based agents with reasoning, learning, and communication capabilities. Figure 1 shows the flowchart of the agent-based solution procedure for a general combinatorial auction problem. It adopts a two-layer hierarchical structure for auctioneer and bidders decision-making.

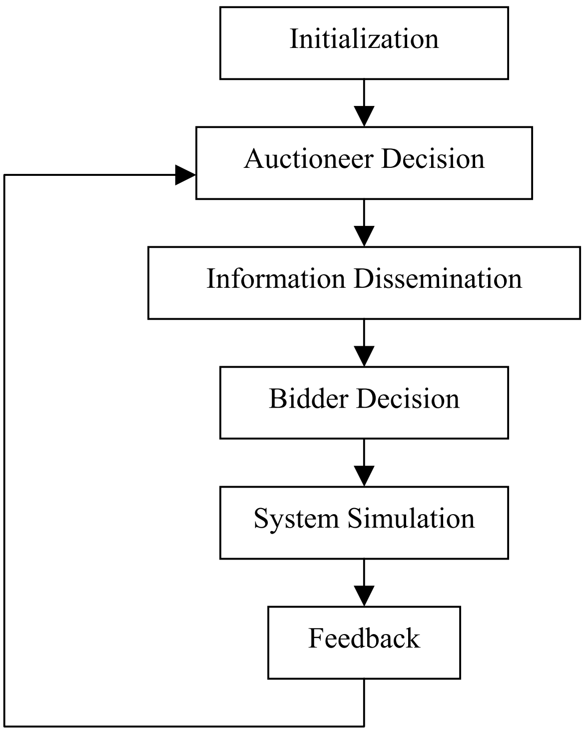

Fig. 1. Flowchart for agent-based combinatorial auction solution procedure

4 Concluding comments

The lack of adequate realism in the modeling of driver behavior is a critical bottleneck restricting the efficient deployment of existing DTA models. In the ATIS scenario, simplified assumptions on driver response to provided information can result in negative impacts on the validity and effectiveness of the information-based control efforts, and potentially deteriorate system performance. The CA approach proposed in this study provides a framework to seamlessly incorporate the information-based control strategy with the consistent understanding of driver behavior heterogeneities and realism. It treats traffic links as commodities, and combinations of traffic links (routes) as bundles of commodities. In the CA process, the decision-making behavior of drivers (bidders) is explicitly considered while the controller (auctioneer) is making information-based control decisions. An ABS approach is proposed to solve the CA problem. The bottom-up configuration of this approach is ideal for the modeling of individual decisions with complex behavior, which is a key property of the CA-based problems for real-time traffic network control with advanced information systems.

References

C. G. Caplice, An Optimization Based Bidding Process: A New Framework for Shipper-carrier Relationships. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA (1996).

S. de Vries and R. V. Vohra, "Combinatorial Auction: A Survey", *INFORMS Journal on Computing 15*, 284-309 (2003).

D. C. Parkes, "Optimal Auction Design for Agents with Hard Valuation Problems", in *Agent Mediated Electronic Commerce II: Towards Next-Generation Agent-Based Electronic Commerce Systems*, A. Moukas, C. Sierra, and F. Ygge (eds), 206-219, Springer, Berlin, 2000.

S. Peeta and S. Gedela, "Real-Time Variable Message Sign-Based Route Guidance Consistent with Driver Behavior", *Transportation Research Record 1752*, 117-125 (2001).

S. Peeta and J. W. Yu, "Adaptability of a Hybrid Route Choice Model to Incorporating Driver Behavior Dynamics under Information Provision", *IEEE Transactions on Systems, Man, and Cybernetics Part A: Systems and Humans 34*, 243-256 (2004).

S. Peeta and A. Ziliaskopoulos, "Foundations of Dynamic Traffic Assignment: the Past, the Present and the Future", *Networks and Spatial Economics 1*, 233-266 (2001).

W. Walsh, M. Wellman and F. Ygge, "Combinatorial Auctions for Supply Chain Formulation", *Proceedings of the 2nd ACM Conference on Electronic Commerce*, 260-269, Minneapolis 2000.