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On activity-based network design problems ☆

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ABSTRACT

This paper examines network design where OD demand is not known a priori, but is the subject of responses in household or user itinerary choices to infrastructure improvements. Using simple examples, we show that falsely assuming that household itineraries are not elastic can result in a lack in understanding of certain phenomena; e.g., increasing traffic even without increasing economic activity due to relaxing of space–time prism constraints, or worsening of utility despite infrastructure investments in cases where household objectives may conflict. An activity-based network design problem is proposed using the location routing problem (LRP) as inspiration. The bilevel formulation includes an upper level network design and shortest path problem while the lower level includes a set of disaggregate household itinerary optimization problems, posed as household activity pattern problem (HAPP) (or in the case with location choice, as generalized HAPP) models. As a bilevel problem with an NP-hard lower level problem, there is no algorithm for solving the model exactly. Simple numerical examples show optimality gaps of as much as 5% for a decomposition heuristic algorithm derived from the LRP. A large numerical case study based on Southern California data and setting suggest that even if infrastructure investments do not result in major changes in link investment decisions compared to a conventional model, the results provide much higher resolution temporal OD information to a decision maker. Whereas a conventional model would output the best set of links to invest given an assumed OD matrix, the proposed model can output the same best set of links, the same daily OD matrix, and a detailed temporal distribution of activity participation and travel from which changes in peak period OD patterns can be observed.

1. Background

Network design problems (NDPs) are a class of optimization models related to strategic or tactical planning of resources to manage a network (Magnanti and Wong, 1984). Even for purposes of improving road networks for commuters (Yang and Bell, 1998) and despite the complexity of traveler choices (Recker, 2001), NDPs generally assume either static demand at a node (elastic or not) or trip-based origin–destination demand. While this assumption is sufficient in many applications, there is increasing recognition that explicit consideration of travelers' schedules, choices, and temporal decision factors is needed. This need has grown in parallel to three related research trends in network design in the past few years: (operational) network design with dynamic assignment considerations when considering only peak period effects, (tactical) service network design with schedule-based demand under longer periods of activity, and (planning) facility location problems that explicitly

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consider the effects that they have on decisions related to routing and scheduling of vehicles. At the planning level, these NDPs have often been based on private firm decisions, rather than on household-based urban transportation planning considerations.

The rationale behind dynamic network design problems is rooted in bi-level NDPs that feature congestion effects. These NDPs operate primarily in civil infrastructure systems, as other types of networks do not generally share the same ''selfish travelers'' assumptions. In this paradigm, the performance of infrastructure improvements is assumed to depend primarily on the route choices of travelers (the commuter) during peak periods of travel, which in turn depend on the choices of other travelers. The dynamic component further allows modelers to assess intelligent transportation systems (ITS) that require more realistic modeling of traffic propagation obeying physical queuing constraints and information flow. Some examples include the stochastic dynamic NDP from Waller and Ziliaskopoulos (2001), Heydecker's (2001) NDP with dynamic user equilibrium (DUE), the linear DUE-NDP (Ukkusuri and Waller, 2008), dynamic toll pricing problem with route and departure time choice (Joksimovic et al., 2005), and the reliability maximizing toll pricing problem with dynamic route and departure time choice (Li et al., 2007). Although these NDPs are especially useful for ITS evaluation and operational strategies, they focus primarily on choices made over a single trip.

Tactical level NDPs tend to place more emphasis on time use and scheduling over congestion effects. Tactical service NDPs (Crainic, 2000) are a specific class used to manage fleets of vehicles with such temporal decision variables as service frequency. However, most of these NDPs focus on the schedules of the service being provided, rather than on incorporating the demand-side schedules of the travelers/users as endogenous elements of the design. Despite the incorporation of temporal effects, most service NDPs assume trip-based demand. There has been a surge of research in schedule-based transit assignment (as opposed to NDP), where travelers' departure time choices are handled explicitly. Tong and Wong (1998) formulated such a model with heterogeneous traveler values of time. Poon et al. (2004) presented a dynamic equilibrium model for schedule based transit assignment. Hamdouch and Lawphongpanich (2008) developed a schedule-based transit assignment model that accounts for individual vehicle capacities. They proposed one of the few schedule-based service network design problems, in the form of a transit congestion pricing problem that models passengers' departure time choices (Hamdouch and Lawphongpanich, 2010). Their model uses a time-expanded network and considers fare pricing to optimize the distribution of travelers within specific capacitated transit vehicles. The origin–destination (OD) demand remains as fixed trips, and not as linked itineraries.

Despite having the greatest need for such consideration, there are no NDP models at the planning level that consider routing and scheduling choices of travelers. It has long been acknowledged that models of traveler activities and time use are much more accurate than statistical trip-based approaches (Recker, 2001; Pinjari and Bhat, 2011). Activity consideration can bring about a tighter integration of infrastructure investment with land use planning and demand management strategies. Activity-based models can capture realistic impacts on travelers that are not limited to single trips but rather to chains of trips and activities forming detailed daily itineraries. Historically, the bulk of activity-based models have been designed as econometric models that do not account for network routing and scheduling mechanisms. The emerging trend in seeking to integrate network characteristics has been to force an interaction with a dynamic traffic assignment problem (e.g. Lin et al., 2008; Konduri, 2012). However, this approach still ignores the network constraints present in scheduling and selection of activities for a household. There have been two primary exceptions to this approach. The first is the disaggregate activity route assignment model (HAPP) pioneered by Recker (1995), with subsequent studies on dynamic rescheduling/rerouting of those itineraries Gan and Recker (2008) and calibration of the activity route assignment models (Recker et al., 2008; Chow and Recker, 2012). The second is the aggregate time-dependent activity-based traffic assignment model (Lam and Yin, 2001; Fu and Lam, 2013). Both modeling frameworks address the issue of activity scheduling, although Lam and Yin's model gives up disaggregate itinerary route choices and trip chains in favor of capturing congestion effects.

Although the transportation planning field has not seen any significant NDP research that models traveler routing and scheduling, the private logistics field has. One such model is the location routing problem (LRP), formulated and solved by Perl and Daskin (1985). The LRP is a set of inter-related problems that includes a facility location problem. What distinguishes LRPs from other facility location problems is that it does not assume that demand to a node is accessed through a single round trip. Instead, a lower level vehicle routing problem is embedded in the model to satisfy demand nodes in the most efficient manner, subject to where the facilities are located. In essence, it is an integrated NDP that accounts for responsive routing and scheduling. Numerous studies have been conducted on variants of the problem or on applications in industry. Several literature reviews have been published, including one from Min et al. (1998) and a more recent contribution by Nagy and Salhi (2007). Problem types developed over the years that may be applicable to activity-based network design in transportation planning include: stochastic LRP (Laporte and Dejax, 1989), where there is more than one planning horizon with time-dependent customer locations and demand; LRP with a mixed fleet Wu et al. (2002) for multimodal network consideration; location-routing-inventory (Liu and Lee, 2003) for modeling activity types as inventory-based needs that are fulfilled periodically; and LRP with nonlinear costs (Melachovsky et al., 2005) that may provide means to incorporate congestion effects at link or activity node level. Readers are referred to Nagy and Salhi's paper for further details. One direct application of LRP with a truck fleet replaced by household travelers is shown by Kang and Recker (2012). They use HAPP as a routing subproblem in a hydrogen vehicle refueling station LRP that allows the behavioral impacts of households' responses to located facilities to reflect siting decisions.

Given the increasing realization that transportation planning needs to reflect travelers' preferences at the level of the activity, we make a parallel observation to Perl and Daskin—that in the transportation planning field there is also a need