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Joint optimization of freight facility location and pavement infrastructure rehabilitation under network traffic equilibrium

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ABSTRACT

Establishment of industry facilities often induces heavy vehicle traffic that exacerbates congestion and pavement deterioration in the neighboring highway network. While planning facility locations and land use developments, it is important to take into account the routing of freight vehicles, the impact on public traffic, as well as the planning of pavement rehabilitation. This paper presents an integrated facility location model that simultaneously considers traffic routing under congestion and pavement rehabilitation under deterioration. The objective is to minimize the total cost due to facility investment, transportation cost including traffic delay, and pavement life-cycle costs. Building upon analytical results on optimal pavement rehabilitation, the problem is formulated into a bi-level mixed-integer non-linear program (MINLP), with facility location, freight shipment routing and pavement rehabilitation decisions in the upper level and traffic equilibrium in the lower level. This problem is then reformulated into an equivalent single-level MINLP based on Karush–Kuhn–Tucker (KKT) conditions and approximation by piece-wise linear functions. Numerical experiments on hypothetical and empirical network examples are conducted to show performance of the proposed algorithm and to draw managerial insights.

1. Introduction

Industrial land-use developments or expansion of existing facilities, especially those in congested urban/suburban areas, often result in increased freight shipment traffic (e.g., heavy trucks) in the neighboring transportation network. This not only increases network congestion and causes delay to the existing traffic, but also accelerates the deterioration of pavement and ride quality (AASHTO and TRIP, 2009), as pavement distresses from heavy trucks are generally orders of magnitude larger than those from passenger cars. Rapid loss of pavement serviceability (e.g., surface roughness) often requires frequent rehabilitation activities and imposes high user and agency costs. For instance, Iowa's growing renewable energy industries have had significant impacts on the quality of its transportation infrastructure. It was reported that pavement repairs and maintenance costs in multiple Iowa counties had increased significantly during and after the construction of biofuel production plants (Gkritza, 2010). In southwest Kansas, the development of large meat processing plants induced heavy truck traffic for shipping processed meat, meat byproducts, grain, and other related products, causing traffic congestion, significant pavement damage, and frequent pavement maintenance in the region (Bai et al., 2010). Another example is the Port of San Francisco (the western edge of the San Francisco Bay near the Golden Gate Bridge), whose heavy cargo traffic and ship repair business have caused high levels of pavement damage on its highway lanes (Caltrans, 2012). In Pennsylvania, the

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heavy truck traffic induced by the emerging natural gas industry has caused severe damages on state roads, forcing the industry to spend more than $ 500 million statewide on pavement repair and replacement (Kyle, 2013). Such unintended consequences of freight facility development increase the social cost of the general public (e.g., due to traffic delay and highway maintenance), and in turn have a negative impact on the efficiency of those freight shipments associated with these facilities. Hence, the design of new industrial facility locations should simultaneously account for the major impacts of freight shipment distribution on the existing highway infrastructure networks (including traffic congestion and pavement deterioration). These endogenous relationships are illustrated in Fig. 1, and some of them have long been overlooked in the literature. While the industry, pavement maintenance agency, and users may be non-cooperative decision makers, proper mechanisms could be developed to provide the industry with incentives to evaluate potential impacts of freight-oriented land-use development plans toward minimal negative social impacts.

The facility location problem has been extensively studied; e.g., see Drezner (1995) and Daskin (1995) for systematic reviews of classic discrete location models. Most research efforts consider distance as the measure of transportation cost (e.g., Graves and Willems, 2005); however, in recent years, researchers started to incorporate the impact of congestion (e.g., travel time) into facility location design. For instance, Konur and Geunes (2011) studied a competitive facility location problem subject to distribution network congestion. Jayaram (2005) evaluated the impacts of roadway congestion on manufacturers, distributors, and the existing supply chains. López and Monzón (2010) developed strategic shipment plan models that integrate sustainability issues into facility location planning and spatial and regional economic analysis. Bai et al. (2011) and Hajibabai and Ouyang (2013) analyzed the interactions among biofuel refinery location, shipment routing under network congestion, and network capacity expansion decisions. Bai et al. (2012) considered a decentralized biofuel supply chain system under biomass market equilibrium in which farmers and biofuel manufacturers are non-cooperative decision makers. Recently, Wang et al. (2013b) addressed biofuel consumption mandates with renewable identification numbers. However, despite all these efforts, the influences of the induced freight traffic on the deterioration and maintenance of pavement infrastructure have not been addressed.

In the broader context of transportation network design, travelers' individual route choices under congestion are often addressed in the form of traffic equilibrium. Abdulaal and LeBlanc (1979) formulated the network design problem (NDP) with equilibrium constraints as an unconstrained non-linear optimization problem. Yang and Bell (1998) reviewed variants of the NDP models under different objective functions and a variety of algorithms (such as the iterative-optimization-assignment algorithm, the link usage proportional based algorithm and the sensitivity analysis-based algorithm). Later, the same authors proposed an equivalent single-level formulation to the bi-level NDP by taking advantage of the continuous and differentiable properties of the implicit user-equilibrium (UE) constraints. A gap function was created, for which an augmented Lagrangian method can be employed to give an exact local solution (Meng et al., 2001). Ban et al. (2006) further extended this idea by transforming the lower level problem into a complementarity slackness condition for a single-level problem and used a Gauss–Seidel decomposition scheme to resolve the possible dimensionality issues. In general, the NDP under UE is a difficult problem because it is NP-hard in its general form (Johnson et al., 1978), and it often involves a large number of variables. Widely considered as a variant of the mathematical programs with equilibrium constraints and discrete variables (DC-MPEC) (Bai et al., 2013; Hu et al., 2008, 2012), the problem is often formulated into a linear/quadratic program with linear complementarity constraints.

Some recent studies made efforts to develop exact global algorithms to solve discrete and continuous NDPs, mainly by reformulating the bi-level problem into an equivalent one with a single-level structure (Lu, 2006; Li et al., 2012; Wang et al., 2013a; Farvaresh and Sepehri, 2011, 2013). For instance, Lu (2006) proposed an exact integer optimization approach for network design problems under UE and deterministic travel demand which is transferred into a quadratic objective, linear constraints problem and solved by an iterative algorithm. Later, Shen and Wynter (2011) proposed a single-level convex optimization formulation to approximate the bi-level structure; their method can be considered as a special case

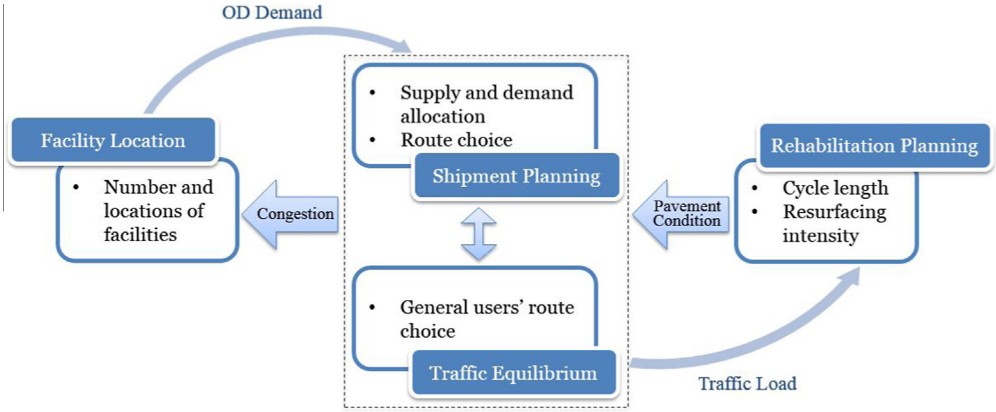

Fig. 1. Interactions among facility location, freight shipment, public traffic, and pavement rehabilitation.