A quantitative and systematic methodology to investigate energy consumption issues in multimodal intercity transportation systems

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ABSTRACT

Energy issues in transportation systems have garnered increasing attention recently. This study proposes a systematic methodology for policy-makers to minimize energy consumption in multimodal intercity transportation systems considering suppliers' operational constraints and travelers' mobility requirements. A bi-level optimization model is developed for this purpose and considers the air, rail, private auto, and transit modes. The upper-level model is a mixed integer nonlinear program aiming to minimize energy consumption subject to transportation suppliers' operational constraints and traffic demand distribution to paths resulting from the lower-level model. The lower-level model is a linear program seeking to maximize the trip utilities of travelers. The interactions between the multimodal transportation suppliers and intercity traffic demand are considered under the goal of minimizing system energy consumption. The proposed bi-level mixed integer model is relaxed and transformed into a mathematical program with complementarity constraints, and solved using a customized branch-and-bound algorithm. Numerical experiments, conducted using multimodal travel options between Lafayette, Indiana and Washington, D.C. reiterate that shifting traffic demand from private cars to the transit and rail modes significantly reduce energy consumption. Moreover, the proposed methodology provides tools to quantitatively analyze system energy consumption and traffic demand distribution among transportation modes under specific policy instruments. The results illustrate the need to systematically incorporate the interactions among traveler preferences, network

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structure, and supplier operational schemes to provide policy-makers insights for developing traffic demand shift mechanisms to minimize system energy consumption. Hence, the proposed methodology provide policy-makers the capability to analyze energy consumption in the transportation sector by a holistic approach.

Keywords: bi-level optimization model; energy consumption; multimodal transportation systems.

1. BACKGROUND AND MOTIVATION

The current transportation system relies heavily on non-renewable fuel energy. It accounts for 71 percent of the nation's petroleum use and 30 percent of U.S. greenhouse gas emissions [12] [30]. These statistics suggest that reducing the energy consumption in the transportation sector can significantly enhance national energy security and help control greenhouse gas emissions. However, the current transportation system is central to the U.S. societal mobility and commerce and cannot be easily or quickly altered. Therefore, reducing the transportation system energy consumption without sacrificing mobility needs disproportionately is a key imperative, and motivates the current study.

The total energy consumption of the current transportation system is a function of the fuel efficiency of the transportation modes and the intensity of transportation mode usage [20]. Accordingly, a comprehensive approach is required to simultaneously: (1) avoid increased traffic activity and reduce current demand for transport; (2) shift demand to more efficient modes of transport such as public transit, walking, cycling and freight rail; and (3) improve the use of fuel efficient vehicles. The International Energy Agency [8] summarized these three principles in an Avoid-Shift-Improve (ASI) approach, which provides a holistic framework for strategic actions to foster sustainable transport systems. This study focuses on the commonly-addressed demand-side strategy of shifting traffic demand from low fuel efficiency modes to high fuel efficiency modes. Empirical data indicates that cars and light trucks used for personal travel alone account for the majority of fuel consumption in the transportation sector [12]. The fuel efficiency of transportation modes (per passenger per gallon) degrades in the order of rail, road, and air modes [27]. Hence, to reduce energy consumption in current transporting systems, the primary focus is on shifting the passenger traffic demand in cars, light-duty trucks, and air to high occupancy modes such as rail and public transit [28]. This raises the key question of how to foster such a traffic demand shift among different transport modes.

Strategic policies which influence transportation supplier actions as well as traffic mode choices represent a promising solution paradigm to realize the demand shift from low fuel efficiency modes to higher efficiency ones. Thereby, the three key players including the travelers (who form the traffic demand), transportation suppliers (who provide the traffic supply options), and policy-makers (who design and implement policy instruments), work independently in the short-term, but interactively in long-term to address energy consumption in the transportation sector. For example, transportation suppliers (who provide vehicles, fuel and traffic infrastructure, and