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Trading off costs, environmental impact, and levels of service in the optimal design of transit bus fleets

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ABSTRACT

The development of a systematic framework to support the design of transit bus fleets is justified by the significant and long-lasting implications associated with decisions to purchase transit vehicles, as well as by developments in fuel propulsion and battery technologies over the last 2 decades that have increased the options available to transit operators, and, in turn, the complexity of assessing the corresponding tradeoffs. The need to evaluate these tradeoffs is, in part, driven by the emergence of environmental impact mitigation, i.e., emissions reductions, as a critical concern of transit operators and governments around the world.

To address these concerns, we present an optimization model to support the design of transit bus fleets while accounting for costs, level-of-service requirements, and environmental impact. Methodologically, the work bridges applications of Economic Input-Output analysis to conduct environmental lifecycle assessment, with seminal work in production economics.

We apply the framework to support design of bus fleets consisting of 4 bus types differing in their fuel-propulsion technology: ultra-low sulfur diesel, hybrid diesel-electric, compressed natural gas, and hydrogen fuel-cell. The 4 bus types were assessed in the National Renewable Energy Laboratory transit bus evaluation and demonstration studies conducted over the period 2003–2009. The nominal problem herein is to minimize acquisition, operation and disposal costs. Constraints in the model are used to impose a minimum frequency of service, i.e., headway, and to ensure that route capacity satisfies passenger demand. Environmental impact is considered along the following dimensions: energy consumption, and emissions of greenhouse gasses, particulate matter, and nitrous oxides. Results show that fleet heterogeneity increases in scenarios where demand fluctuates, i.e., peak vs. off-peak. Perhaps even more interesting, we show how the dual/shadow prices provide a (monetary) measure of the tradeoffs among level of service and environmental impact, and discuss how they can be used to obtain robust fleet configurations.

1. Introduction

The decision to purchase transit vehicles has long-lasting implications for the lifecycle costs, emissions, and level of service provided by a transit agency. Perhaps, because the variety of buses is relatively low, and because of the increased complexity of managing heterogeneous fleets, the literature on bus fleeting is not extensive. However, as technology has developed, buses have grown increasingly heterogeneous in a variety of important metrics, including capacity, price, and operating characteristics. Recent and projected advances in alternative fuel and battery technologies have added an interesting dimension that will be relevant for the

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foreseeable future. The practical motivation for our work, therefore, related to the complexity of decisions facing agencies in terms of assessing the relevant tradeoffs.

Methodologically, the work builds on Croft McKenzie and Durango-Cohen (2010), and bridges applications of Input-Output (IO) analysis to conduct environmental lifecycle assessment (LCA), with seminal work in production economics. In the latter, product design, production planning and scheduling problems are frequently formulated as IO models with substitution, and subsequently analyzed and solved as linear programs (cf. Shephard, 1953; Hackman and Leachman, 1989). Indeed, and as described in Koopmans (1951), these types of problems are among the first applications of linear programming. In addition to providing decision-support, the framework provides a well-established approach to conduct sensitivity analysis, i.e., to evaluate the effect of perturbations in the inputs on the results.

We apply the framework to support design of bus fleets consisting of 4 bus types differing in their fuel-propulsion technology: ultra-low sulfur diesel, hybrid diesel-electric, compressed natural gas, and hydrogen fuel-cell. The 4 bus types were assessed in the National Renewable Energy Laboratory transit bus evaluation and demonstration studies conducted over the period 2003–2009. Data are also from the environmental LCA in Croft McKenzie and Durango-Cohen (2012). The nominal problem herein is to minimize acquisition, operation and disposal costs. Constraints in the model are used to impose a minimum frequency of service/maximum headway, and to ensure that capacity satisfies passenger demand. Environmental impact is considered along multiple dimensions. Results show that fleet heterogeneity increases in scenarios where demand fluctuates, i.e., peak vs. off-peak. Perhaps even more interesting, we show how the dual/shadow prices provide a (monetary) measure of the tradeoffs among level of service and environmental impact, and discuss how they can be used to obtain robust fleet configurations.

The remainder of the paper is organized as follows. In the next section, we provide a brief review of the relevant literature. A formulation capturing the tradeoffs in designing bus fleets is presented in Section 3. Data used in the present study are presented in Section 4. In Section 5, we consider a number of scenarios where the optimization model is used to select bus fleets. Discussion of the results and conclusions of the study are presented in Section 6.

2. Background

Two streams of literature are related to the work presented herein. On the one hand, planning models aimed at capturing the tradeoffs between costs and level-of-service, i.e., capacity and frequency/headway; and on the other hand, environmental LCAs of transit vehicles.

In planning models, decisions to purchase a given type and number of buses are usually subordinated to routing and scheduling problems. That is, the number of buses to satisfy demand is derived for a given level of service and bus route/schedule, and under the assumption of homogenous bus type/technology. Hauer (1971) and Navin (1979) are pioneering studies. Vuchic (2005) is, perhaps, first to examine heterogeneity in bus capacity: either high or low capacity, with corresponding price and operating cost differences. In addition to costs, tradeoffs between the buses are explored along the following dimensions for peak and off-peak service: frequency/headway, passenger wait and load factors. Hsu and Wu (2008) builds on the aforementioned models and proposes a fleet size model for number of cars per train or BRT platoon. Other approaches to support bus fleeting include Khasnabis et al. (2003) and Peet et al. (2009). The former studies optimal replacement schedules to meet long-term fleet needs. The latter proposes a tool to allow transit operators to explore the tradeoffs between different bus technologies.

Environmental LCA of transportation and transit vehicles is an ongoing field of research. Chester and Horvath (2009) has compiled what is, perhaps, the most comprehensive look at transit vehicles to date. Another substantial evaluation of previous LCAs is presented in MacLean and Lave (2003). However, research that accounts for the operating characteristics of alternative fuel vehicles is still in its early stages, in part, because deployment of such vehicles is not widespread, and thus, (field) data are not widely available. Most studies on alternative fuel vehicles have focused on automobiles and on tailpipe emissions. Findings on alternative fuels in transit vehicles are mixed. In one of the first studies to relate environmental and economic costs, Johansson (1999) used lifecycle emissions calculations to look at economic efficiency. He found that CNG buses can result in fuel savings of up to 35%. Hess (2007) reports that, although purchase price gaps were declining between CNG and diesel buses, higher labor and maintenance costs are still significant. In a review of GHG-tailpipe emission and vehicle LCAs, Hesterberg et al. (2009) concluded that these mixed results are, in part, attributable to the complexity and uncertainty involved in measuring the lifecycle emissions associated with a vehicle.

Various approaches have been used to conduct the LCAs, with economic IO models, labeled EIO-LCAs, constituting an appealing one (Hendrickson et al., 2006). Rather than mapping processes in detail, e.g., chemical reactions, the IO approach involves specifying the requirements or bill of materials of a product in terms of demand for economic sectors such as transportation, construction, or financial services. The model, in turn, is used to compute the economic activity and environmental repercussions associated with satisfying the given demand for the product. Because all sectors represented in the economy are linked, there is no effective boundary on the scope of the analysis. The number and diversity of EIO-LCAs has greatly increased since the late 1990s as a result of the methodology's flexibility, simplicity, and, importantly, the availability of tools and models to support the analysis. Examples can be found in the fields of waste disposal (Kondo and Nakamura, 2004), transportation (Facanha and Horvath, 2007), and service industries (Hendrickson et al., 2006). Although they have provided much insight, EIO-LCAs have been used almost exclusively as descriptive tools. That is, EIO-LCA models have not been integrated into a prescriptive framework to support decisions that arise during product/process design or (production) planning. To address this limitation, we build on the model of Croft McKenzie and Durango-Cohen (2010), and use it to address the problem of designing bus fleets.