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Urban bus fleet-to-route assignment for pollutant emissions minimization

Felipe Jiménez *, Alfonso Román

University Institute for Automobile Research (INSIA), Technical University of Madrid, Ctra. de Valencia km. 7, 28031 Madrid, Spain

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ABSTRACT

This study proposes a methodology to optimize the assignment of an urban bus fleet to a set of fixed routes, taking into account the differences among routes and the differences among vehicle types and propulsion technologies in order to reduce pollutant emissions (CO_2, CO, THC, NO_x and PM). A Mixed Integer Linear Programming optimization model is stated and two scenarios are assessed: minimization of CO_2 and NO_x. The results show that it is feasible to obtain a fleet distribution in which emissions for any given pollutant are reduced without increase in emissions of other pollutants.

1. Introduction

Over the last ten years, policy makers have given increasing attention to the efficient use of energy and the improvement of air quality. Vehicle traffic emits substances which pollute the atmosphere and contribute to global warming (Chapman, 2007; Gurjar et al., 2008). In the case of Madrid, the inventory of pollutant gases reveals that during 2012, road transportation caused 32.7% of greenhouse gas emissions, 53.7% of NO_x generation, 13% of the non-methane volatile organic compounds, 45.3% of CO and 67.3% of particulate matter (PM) with a diameter of less than 10 μm (MCC, 2014).

In order to ease pollution in urban centers, some measures frequently used by legislators consist in establishing low emission zones (Boogaard et al., 2012), promoting the utilization of public transportation systems (Buehler and Pucher, 2012), developing a non-motorized transport infrastructure (Kim and Dumitrescu, 2010), and stimulating vehicle fleet renovation and improving its maintenance conditions (Zachariadis et al., 2001). In particular, Madrid's Air Quality Plan 2011–2015 (MCC, 2012) proposes 70 measures to reduce pollution levels regarding different economic sectors, and more than 10 are related to urban bus transport, such as general use of bus lanes, introduction of new propulsion technologies in buses that moves in the low emissions zone, etc. However, these kinds of solutions requires significant economic investments (Creutzig and He, 2009), broad time intervals (EEA, 2011) and, quite frequently, after completion, the achievements are difficult to identify and evaluate (Lake and Ferreira, 2002), so the proposal of novel low-cost but efficient measures would be a challenge.

The research reported in this paper is more modest in scope and cost than the initiatives outlined above. It focusses on the assignment of vehicles to routes, seeking a close match between bus technologies and the characteristics of the routes that

* Corresponding author. Tel.: +34 913365317; fax: +34 913365302.
E-mail address: felipe.jimenez@upm.es (F. Jiménez).

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they serve, so as to minimize emissions of relevant pollutants. So far as we are aware, no research has been published on this assignment task, even where the focus is on non-environmental criteria. Research within the broader context of bus operations planning and environmental objectives is however of general interest and is reviewed in the next section.

2. Background

Vehicle fleet planning has been studied from diverse perspectives, differentiating, in this context, operational considerations and environmental impact, although both aspects may converge. For instance, emission levels and fuel consumption are closely related to the distance traveled; therefore an optimization intended to minimize aggregate travel distance may be expected to generally provide more favorable results from an environmental standpoint. McKinnon et al. (2010) analyze the environmental consequences of logistics, highlighting that vehicle routing and scheduling are factors which influence the economic and environmental performance of a distribution system, and have a potential to contribute to greenhouse gas and other pollutant emissions reduction. Furthermore, local conditions determine the precise form of the planning task in any given scheme, and this circumstance could condition the selection and assignment of the vehicles to their routes or services. A classical approach consists in designing routes to be traveled by the vehicles of a logistic company in order to accomplish the delivery of goods to a set of customer locations at a minimal cost. This problem is known as the Vehicle Routing Problem (Dantzig and Ramser, 1959). Its framework admits multiple alternatives (Kumar and Panneerselvam, 2012) and different methodologies for its resolution (Laporte, 1992).

On the other hand, significant efforts have also been dedicated to developing methodologies for optimal route and bus headway design with the intention of minimizing the system's total cost, while providing an adequate customer service level (Byrne and Vuchic, 1971; Mandl, 1980; Spasovic and Schonfeld, 1993; Chien et al., 2003). The complete planning process of a bus operation consists of five phases: (i) design of the route network, (ii) setting the journey frequencies, (iii) timetable planning, (iv) bus scheduling, and (v) driver arrangement (Ceder and Wilson, 1986). This problem has a high degree of complexity, but it is arguably incomplete in its coverage of bus operations planning, in that it does not include the assignment of vehicles to routes, which is the primary focus of the present paper. A variety of metaheuristic techniques have been applied to specialized tasks concerned with bus fleet planning, route planning and operational management; for example genetic algorithms (Pattnaik et al., 1998; Afandizadeh et al., 2013), simulated annealing (Han et al., 2005) and bee colony optimization (Nikolić and Teodorović, 2013) during its resolution. Specific versions for the layout of school routes appear in Bowerman et al. (1995) and Spasovic et al. (2001).

Another optimization problem category frequently posed in bus transportation planning consists in assigning each vehicle to the most adequate depot in order to minimize the distance traveled by the fleet (Sharma and Prakash, 1986; Djiba et al., 2012). In this analysis it is assumed that, every vehicle has been previously allocated to a particular route and the depot's capacity is also known. The main drawback of this approach is that the distance proportions associated with pull-out and pull-in trips to and from the depot are not very significant in comparison with the total range traveled during daily operation. Therefore, the fleet's performance throughout the most representative time period is not evaluated.

Alam et al. (2014) examine the impact of transit improvement strategies on bus emissions along a busy corridor in Montreal. Smart cards, limited-stop (express bus) service and reserved bus lane measures applied by the system's operator are assessed, estimating bus pollutant emissions at three levels: road segment, bus stop and per passenger. Its effects on emissions and idling time reductions are discussed. Alam and Hatzopoulou (2014) analyze the effects of transit signal priority, queue jumper lanes and the relocation of bus stops on bus emissions using simulation with two alternative fuels: diesel and compressed natural gas (CNG).

Concerning fleet renewal, Figliozzi et al. (2013) propose a methodology to select the optimal replacement strategy taking into account the investment in vehicle acquisition, operating costs and the savings derived from emission reductions.

André and Villanova (2004) evaluate urban bus operation and its impact on emissions, surveying the bus network in Paris using two methods to appraise and classify the routes: the first approach uses statistics related to route characteristics, travel time, commercial speed, annual statistical data and the irregularity of travel and information on the problems encountered; while the subsequent procedure considers other aspects related with the socioeconomic peculiarities of each route's setting. In André et al. (2005), the influence of the vehicle's operating conditions on the generation of pollutant emissions is assessed.

In summary, bus operations and management have been well-studied with respect to conventional optimization criteria (cost, ridership, accessibility, etc.), but with little attention so far to environmental performance. This paper is concerned specifically with the assignment of vehicles to routes, taking into account which types of vehicles are more appropriate with respect to the peculiarities of each route for reducing emissions. Considering that not all routes within a city have similar characteristics, our approach is focused on a detailed matching of relevant vehicle attributes to inferred attributes of routes, in a fine-grained analysis which can yield significant environmental benefits.

3. Methodology

The methodology is based on the information related to the kinematic performance of each vehicle type on every route. In order to perform a fine-grained analysis, the vehicle's operational driving cycle is segmented into microcycles and