Strategic fleet planning for city logistics

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\textbf{A B S T R A C T}

We study the strategic problem of a logistics service provider managing a (possibly heterogeneous) fleet of vehicles to serve a city in the presence of access restrictions. We model the problem as an area partitioning problem in which a rectangular service area has to be divided into sectors, each served by a single vehicle. The length of the routes, which depends on the dimension of the sectors and on customer density in the area, is calculated using a continuous approximation. The aim is to partition the area and to determine the type of vehicles to use in order to minimize the sum of ownership or leasing, transportation and labor costs. We formulate the problem as a mixed integer linear program and as a dynamic program. We develop efficient algorithms to obtain an optimal solution and present some structural properties regarding the optimal partition of the service area and the set of vehicle types to use. We also derive some interesting insights, namely we show that in some cases traffic restrictions may actually increase the number of vehicles on the streets, and we study the benefits of operating a heterogeneous fleet of vehicles.

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\section{Introduction}

Urban areas are characterized by a high concentration of small commercial activities which generally results in a very high number of vehicles movements, often uncoordinated and performed with less-than-truckload shipments. The concept of \textit{city logistics} (Ehmke, 2012) recognizes the need for efficient and environmentally-conscious urban transportation policies that can improve the efficiency of transportation systems as well as reduce energy consumption and vehicles emissions. One example is the introduction of electric vehicles into logistics fleets (Roumboutsos et al., 2014). Because of their high densities and relatively short distances, cities are particularly well-suited to the early adoption of alternative types of mobility ((European Commission, 2013), such as electric vehicles.

In order to provide incentive for investment in new low energy consumption vehicles and encourage their use, several cities have enacted regulations regarding urban freight transport. These often take the form of access limitations to certain types of vehicles at certain times of the day, depending on vehicle characteristics such as dimension, type of energy consumed, engine type, etc. (Muñuzuri et al., 2005). For example, in the Dutch city of ’s-Hertogenbosch, green and silent trucks are allowed to enter the city center at any time, whereas other commercial freight vehicles are admitted only between 7:00

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and 12:00, and between 18:00 and 20:00. Italian cities such as Rome, Milan, Bologna and Florence, now restrict the access of diesel vehicles to the city center at certain times of the day (e.g. from 7:00 to 20:00 in Bologna).

Faced with increasingly restrictive access regulations and with the need to reduce costs, energy use and greenhouse gas emissions, logistics service providers are looking for ways to better manage their vehicles fleet. Stewart (2012) reports that about half of the organizations he surveyed would be willing to pay a 10% premium ownership cost for an electric vehicle, due to fuel savings, CO₂ reduction and “green branding” effect.

While there exists a rich body of literature on the fleet composition problem at the operational level, e.g. Golden et al. (1984) and Koç et al. (2014), relatively little has been done at the strategic level. One of the first publications of the fleet composition problem is due to Kirby (1959) who considers a homogeneous fleet. Loxton and Lin (2011) study a multi-period heterogeneous fleet dimensioning problem in which the cost function is the sum of fixed, variable and hiring costs. They assume that the number of vehicles of a given type required in a certain period is known. Loxton et al. (2012) investigate a stochastic version of the problem, in which the future vehicle requirements follow a given probability distribution. Both studies present a solution methodology based on dynamic programming and the golden section rule. Jabali et al. (2012) develop a continuous approximation model for the heterogeneous fleet composition problem and provide a mixed integer non-linear formulation along with upper and lower bounding procedures. Their study is the first to incorporate operational aspects, such as vehicles routes, within a strategic decision model. Finally, Nourinejad and Roorda (2016) extend the study of Jabali et al. (2012) for radial networks.

In this paper, we consider the strategic problem of determining an optimal fleet composition for a logistics service provider making deliveries to an urban area in the presence of access restrictions for certain types of vehicles. These restrictions take the form of a maximum length of time that each vehicle type can spend in the service area. The problem is to determine the number and types of vehicles to use in order to minimize the sum of ownership or leasing, transportation and labor costs without exceeding the transportation capacity of the vehicles and the maximum time allowed within the service area. Specifically, we consider a rectangular urban area which is partitioned into contiguous rectangular blocks, each served by a single vehicle. We use a continuous approximation model (Daganzo, 1984a; 1984b; 1987a; 1987b) to calculate the distances traveled. This approach is particularly useful in tackling strategic decision problems since it smooths out the minor dynamic and stochastic variations in the input parameters, as discussed in Francis and Smilowitz (2006) and in Jabali et al. (2012).

Our paper contributes to the literature in several ways. First, we model the strategic problem of managing a heterogeneous vehicle fleet to serve an urban area in the presence of access restrictions. Second, we propose an efficient dynamic programming (DP)-based algorithm to calculate an optimal solution for the case of two types of vehicles (e.g., electric and diesel), and we use a mixed integer linear programming (MILP) formulation for more general settings. Third, we establish structural properties of the optimal partitioning of the service area, such as where to use each type of vehicle. Finally, we show how the optimal fleet composition changes depending on the vehicle parameters, and we discuss the impact of city access restrictions on fleet composition.

The remainder of this paper is organized as follows. In Section 2, we describe the problem and we provide a MILP formulation. In Section 3, we present our DP formulation and derive analytical results: we first consider the single-strip-single-vehicle-type case, then the single-strip-multiple-vehicle-types case, and finally the multiple-strip-multiple-vehicle-type case. In Section 4, we report some numerical results on the impact of city access restrictions and on the benefits of using a heterogeneous fleet of vehicles and compare the performance of our MILP and DP formulations. All proofs are provided in the Appendix.

2. Model

In this section we first describe the problem setting. Subsequently we present the routing strategy and the partitioning policy. Finally, we introduce the MILP formulation.

2.1. Problem setting

The continuous approximation literature proposes two main ways of approximating the shape of service area: a rectangular shape as in Daganzo (1984b); Gaboune et al. (1994); Huang et al. (2013); Newell and Daganzo (1986b) and Ouyang (2007), and a ring-radial shape as in Newell and Daganzo (1986a) and Jabali et al. (2012). In the first case the depot is located outside the area, while in the second one the depot is located in the center. In practice the shape of the zone has no major impact on the quality of the approximation (Daganzo, 1984a; Eilon et al., 1971). Motivated by the widespread policy of operating an urban consolidation center at the entrance of a city (Quak and De Koster, 2006), we model the service area as a rectangular shape and we assume that the depot is located south of the area at a distance φ from the midpoint of its bottom edge (Fig. 1). We refer to the closest edge of the rectangle as the ‘bottom’ edge and the furthest edge as the ‘top’ edge. We also use the term ‘width’ to refer to the size of horizontal edges and ‘length’ to the size of vertical edges, even if the vertical distance may be smaller than the horizontal distance. Because we focus on an urban area, we use the L₁ (Manhattan) norm to calculate distances. A number e of customers are located in this area, and are distributed according to a density function δ(x), where x is a point within the area. As in Daganzo (2005) and Huang et al. (2013), we assume that the density function δ(x) does not vary significantly within the area and therefore, without any significant loss of accuracy,
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