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Optimal allocation of vehicles to bus routes using automatically collected data and simulation modelling

Gabriel E. Sánchez-Martínez [a,*], Haris N. Koutsopoulos [a,b], Nigel H.M. Wilson [a]

[a] Massachusetts Institute of Technology, 77 Massachusetts Ave., Room 1-238, Cambridge, MA 02139, United States
[b] Northeastern University, 563 Holmes, 360 Huntington Ave., Boston, MA 02115, United States

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ABSTRACT

Monitoring the service quality of high-frequency bus transit is important both to agencies running their own operations and those contracting out, where performance measures can be used to assess contract penalties or bonuses. The availability of automatically collected vehicle movement and demand data enables detecting changes in running times and demand, which may present opportunities to improve service quality and fleet utilization. This research develops a framework to maximize service performance in a set of high-frequency bus routes, given their planned headways and a total fleet size constraint. Using automatically collected data and simulation modelling to evaluate the performance of each route with varying fleet sizes, a greedy algorithm adjusts allocation toward optimality. A simplified case study involving morning peak service on nine bus routes in Boston demonstrates the feasibility and potential benefits of the approach. A potential application is automated detection of routes operating with insufficient or excessive resources.

1. Introduction

Most likely, the management of a transit agency has, through careful service planning and performance monitoring, set the fleet size on most routes at an appropriate level. However, the nature of this ongoing task places more emphasis on problem routes; for instance, routes that are suffering delays due to roadwork or routes that are heavily crowded. Management will receive more complaints from passengers using these services, or it might have the initiative to revise resource levels in anticipation of such problems. In the meantime, there may be undetected opportunities to save resources on routes that are performing well and have excess resources, as well as to improve service performance of routes that could greatly benefit from added resources but have not yet received special attention. This research addresses the problem of assigning vehicles to routes of a bus network, given a target headway for each route and a fixed total fleet size, with the objective of maximizing total service performance.

There are a number of factors that affect service performance. Some are in control of the operator at the time of operation, such as the dispatching discipline used at terminals and the set of strategies used to regulate headways. Others, like infrastructure, congestion, and demand for service are considered fixed in the short term. Still others, like scheduled cycle time, are in control of management at the service planning stage. Greater cycle times result in greater recovery times at terminals, thereby making it easier to dispatch vehicles regularly. In the service planning stage, increasing cycle times is an effective strategy to manage running time variability.

Cycle time c is determined by target headway h and fleet size n, through the relationship $c = nh$. Greater cycle times can be achieved by increasing fleet size, increasing headway, or a combination of both. Increasing headway while holding fleet size constant increases cycle time without additional operating cost, but it decreases the passenger carrying capacity of the service, making vehicles more crowded, in addition to increasing passenger waiting times. Although the scheduled cycle time will have increased, dwell times at stops will increase and become more variable, so the net effect could very well be lower service quality if ridership is high. When ridership is relatively low and the operator is struggling to

* Corresponding author.
E-mail address: gsanmar@mit.edu (G.E. Sánchez-Martínez).

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dispatch vehicles at regular intervals, the additional recovery time provided by an increased headway can improve service reliability.

An alternative way to increase cycle times is to increase fleet size while holding the target headway constant. This does increase operational cost, but it adds slack to running times without directly affecting waiting times or loads. If the operator uses the additional resources correctly, headway regularity can improve, which in turn decreases waiting times and balances loads from vehicle to vehicle. Balanced loads can, in turn, reduce running time variability through less variable dwell times. The extra slack can be used at the terminals to improve dispatch regularity, but also en route in the form of holding or slowing vehicles strategically to maintain regular headways. In the latter case, running time variability decreases at the expense of higher typical running times. Increasing fleet size is perhaps the most effective way of dealing with running time variability at the service planning stage.

Of all the factors that affect service quality, only fleet size will be considered in this research. Headway determination responds to a wide range of factors, including policy and network effects. Simultaneous consideration of headway and fleet size would certainly be a more complete approach to optimizing resource allocation, but also a more complex one. The premise of this research is that the target headway of each route has been appropriately set based on service delivery policy and demand for service. The objective is to allocate resources in a way that maximizes service quality in the current set of routes, without altering the service plan.

In this research, optimization is used to allocate a fixed total amount of resources among a group of routes, without changing their frequencies or operating strategies, in a way that maximizes service performance. Optimization has played an important role in planning, frequency determination, and vehicle and crew scheduling for bus transit (Desaulniers & Hickman, 2007; Ibarra-Rojas, Delgado, Giesen, & Muñoz, 2015). The optimization approach followed in this research differs from many past approaches in that it optimizes the allocation of a fixed total amount of vehicles over a group of routes rather than determining frequencies, although the two problems are closely related (Ceder, 1984; Constantin & Florian, 1995; Furth & Wilson, 1981; Li, Wangtu, & Shiwei, 2013; Martínez, Mauttone, & Urquhart, 2014; Verbas & Mahmassani, 2013; Yu, Yang, & Yao, 2010). Han and Wilson (1982) focus on allocation of vehicles in the case of heavily utilized overlapping routes.

Unlike existing work aimed at helping planners obtain the inputs to a manual or computer-aided scheduling process, the framework developed in this research can be applied to automatically monitor high-frequency bus services and detect opportunities to optimize allocated fleet sizes. The framework could benefit large bus agencies with many high-frequency services, and especially agencies that contract out their operations, passing on detailed scheduling responsibilities to private operators while monitoring service quality and occasionally adjusting fleet sizes in contracts to address regular disruptions caused by changing running times and running time variability. London Buses is as example of an agency following this structure.

This paper is organized as follows: Section 2 presents a framework to optimize resource allocation and Section 3 discusses a specific optimization method. The problem is solved separately for each time period (e.g. first the morning peak, then the mid-day, then the afternoon peak, etc.) One of the challenges faced is the systematic variation of running times and headways within each of these time bands. An operator will vary the fleet size of a route according to this, providing the peak vehicle requirement of each time period only when it is needed. Since schedule data is not available for the hypothetical scenarios with smaller or larger fleets, vehicle profiles must be estimated. Section 4 discusses this further and proposes heuristics to overcome the obstacle. Section 5 presents a simple application of the framework and optimization algorithm to a set of nine bus routes. Section 6 closes with a summary and concluding remarks.

2. Framework

Increasing the fleet size of a bus service can enhance an operator's ability to maintain regular headways, thereby improving service performance. It is in everyone's interest to have good performance, but adding resources is feasible only up to the overall fleet size (or budget) constraint. Optimizing resource allocation involves identifying where resources are needed the most. The objective is to find the resource allocation that attains the best overall service performance under an existing service plan, present operating conditions, and specified overall fleet size.

2.1. Service performance

Service performance is a general term that can capture many quantifiable aspects of bus operations. The primary factors relate to service quality as perceived by passengers. For example, performance may include measures of waiting time and crowding. These may be expressed in absolute terms or relative to a performance standard. For example, the average number of minutes of wait experienced by passengers is an absolute measure of waiting time, while excess waiting time is expressed relative to the headway specified in the service plan. Performance measures based on vehicles (rather than passengers) can also be considered. Examples include headway and running time coefficients of variation. Adding vehicles to a route can help prevent late terminal departures, thus decreasing headway variability and passenger waiting times. Moreover, service performance can capture general aspects of operations, such as congestion at terminals due to excess number of vehicles standing.

When multiple criteria are driving the optimization process, the relative importance of each factor must be considered. There may be a situation in which adding a vehicle to one route improves one aspect of service performance considerably while not significantly affecting a second aspect. Adding the vehicle to a different route instead may considerably improve the second aspect of service performance while not affecting the first very much. In such cases, the trade-off between the two aspects must be considered in deciding to which route the vehicle should be allocated.

The performance improvement resulting from adding a vehicle to a route will decrease as fleet size increases. When a route is severely under-resourced, the addition of one vehicle can have a profound impact on service performance. In contrast, when a route has excess resources, the addition of one vehicle might not have visible effects on performance. Fig. 1 illustrates the conceptual relationship between fleet size and the performance of a route. There are four regimes in this relationship, separated by dotted vertical lines. At least one vehicle must be allocated to provide service. Once service is being provided, additional vehicles will bring about performance improvements, albeit at a decreasing rate. The rate will continue to decrease until adding a vehicle does not result in visible performance improvements. While there are no capacity problems as a result of a large fleet size, continuing to add vehicles will not affect performance. However, having an excess number of vehicles can degrade performance if, for instance, there is insufficient capacity at terminals for vehicles to stand and vehicle congestion at terminals is one of the performance factors under consideration. The exact shape of the performance function depends on the factors composing it and the way operators manage the different levels of resource.

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