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An integrated approach for timetabling and vehicle scheduling problems to analyze the trade-off between level of service and operating costs of transit networks

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ABSTRACT

In transit systems there is a critical trade-off between the level of service and operating costs. At the planning level, for a given network design, this trade-off is captured by the timetabling (TT) and vehicle scheduling (VS) problems. In the TT problem we try to maximize the number of passengers benefited by well timed transfers, while in the VS problem we seek to minimize the operating costs, which are related to the fleet size. This paper presents two integer linear programming models for the TT and VS problems, and combines them in a bi-objective integrated model. We propose and implement an ϵ-constraint method to jointly solve this TT and VS bi-objective problem. This allows to analyze the trade-off between these two criteria in terms of Pareto fronts. Numerical experiments show that our proposed approach can solve scenarios with up to 50 bus lines.
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1. Introduction

The bus network planning process can be divided into two main stages. The first one is the *tactical planning* stage where the bus lines are designed and then the timetables (or departure times of all trips) are set. This stage focuses on offering a high level of service for clients: frequency of the lines, waiting times, and short transfers, among others. The second stage is the *operational planning*, where the vehicle and crew scheduling problems are considered. This stage seeks to minimize the operating costs of the transport system. The usual approach to solving the entire planning problem is to develop sequential approaches where one or more problems are solved and the solution is taken as an input of the following sub-problems. Unfortunately, these approaches lead to sub-optimal solutions for the entire plan. Therefore, finding properly integrated approaches for the sub-problems of the transit network planning is a challenging research area where proper formulations and efficient solution methodologies are required. In this study, we focus on the integration of the following two sub-problems of the bus planning process.

- The timetabling problem (TT): this sets the departure times of all trips in order to maximize well-timed passenger transfers at some of the main stops.

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- The vehicle scheduling problem (VS): this determines the set of trips that a vehicle will make during the day in order to reduce the costs based on using the vehicles. In this study, we consider the single depot homogeneous vehicle scheduling problem.

Fig. 1 shows the type of solutions we want to obtain through an integrated approach to the TT and VS problems: here, there are three bus lines starting and ending at the same point. Each line has its own trips from 08:00 to 12:00 each day, and the total round trip lasts one hour. These three lines share the same fleet of 10 buses. The TT line corresponds to the timetabling solution: the departure time of each trip of each line. The VS line is the assignment of the vehicles, that is, which bus is assigned to which trips. For example, vehicle *d* makes trip 1 of line 2, then trip 4 of line 2, and then trip 8 of line 1. Notice that a small change in the timetable can dramatically disturb the vehicle assignments. For instance, suppose that trip 3 of line 1 departs at time 9:02: then vehicle *a* can no longer cover this trip and all the assignments of the vehicles must be reconsidered.

Both of the elements addressed by the previous problems, the level of service (captured by the timetabling) and the operating costs (in terms of vehicle usage) are important in the operation of the transport system. A high level of service guarantees a social benefit, but saving on costs is necessary to have a profitable system. Indeed, timetabling and vehicle scheduling link the level of service with the operating costs, and although a cost–benefit analysis is included in the transit network design process, similar cost–service analyses for the daily operation of a system are missing from the literature. Since the level of service and the operating costs are naturally in conflict, our motivation is to define an approach to take into account the trade-off between these criteria by optimizing the timetabling and vehicle scheduling decisions. To achieve this, we propose a bi-objective optimization approach to integrate the timetabling and vehicle scheduling problems (denoted by TT–VS). In this way, we manage to answer questions such as: how to improve the service at minimum cost? How many passengers are benefited by introducing one more bus to the vehicle fleet? That is, we develop a tool to quantify how much the level of service increases (or decreases) per bus. In this manner, we address one of the main issues of public transport planning, as stated by Ceder (2007):

> "[...] it is desirable to analyze simultaneously the procedures for constructing timetables and for scheduling vehicles. However, because of the complexity of this analysis, the two procedures are treated separately."

The bi-objective methodology of this paper is not only useful to determine incomparable solutions based on passenger transfers and fleet size but also to avoid sequential approaches in order to guarantee optimal solutions considering the degrees of freedom in both the TT and the VS. Our bi-objective optimization problem is solved by an ϵ-constraint method to obtain the exact trade-off curve between well timed passenger transfers and the fleet size. In this manner, we are able to determine the decision of both problems simultaneously, avoiding sequential approaches, and are able to study the compromise between the two criteria of the entire planning process by finding the exact Pareto optimal fronts.

The rest of this article is organized as follows. Section 1.1 reviews some of the literature most closely related to our study. Section 2 presents the definition of the problem and a mathematical formulation for the integrated timetabling and vehicle scheduling approach, TT–VS. Section 3 presents our proposed solution methodology, which is based on a bi-objective integer linear programming solved by an ϵ-constraint method. Section 4 exhibits the exact Pareto fronts for some randomly generated instances. The obtained trade-off solutions are then analyzed to show that our proposed methodology is effective at linking the level of service with the costs. Finally, Section 5 concludes this paper and presents further avenues of research.

1.1. Related literature

Ways of integrating the two sub-problems of the planning process can be divided into two types: sequential integration and complete integration. On the one hand, a sequential integration considers the characteristics of one sub-problem while

	Line 1							
Trips	1	2	3	4	5	6	7	8
TT	8:03	8:33	9:05	9:33	10:00	10:32	11:07	11:40
VS	a	b	a	c	b	a	b	d

	Line 2						
Trips	1	2	3	4	5	6	7
TT	8:01	8:42	9:25	10:02	10:43	11:20	11:58
VS	d	e	f	d	c	e	a

	Line 3											
Trips	1	2	3	4	5	6	7	8	9	10	11	12
TT	8:10	8:32	8:51	9:14	9:31	9:55	10:14	10:35	10:56	11:17	11:40	11:59
VS	f	g	h	i	j	g	h	f	i	h	c	f

Fig. 1. A solution for the TT and VS problems: Three bus lines, each one with its trips from 08:00 to 12:00 each day, and the total duration of each trip is around one hour. These three lines share the same fleet of 10 buses.

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