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Network-wide synchronized scheduling of public transport services

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EXTENDED ABSTRACT

Study Motivation and Objectives

Bus line timetabling is a part of the tactical planning phase which consists of the following stages: (i) frequency settings; (ii) timetable design; (iii) vehicle and crew scheduling ([7], [3], [1]).

Timetables are usually determined with the objective of minimizing passenger waiting times at stops [4]. Several studies have considered also the minimization of the waiting times of passengers at transfer stops as an additional metric for reducing the total travel time of passengers.

The problem of timetable synchronization has been addressed by [2], [6], [11], [10] with the objective of reducing the waiting time of passengers at the transfer stops while maintaining even dispatching headways among the daily trips. Most works in the literature have decoupled the timetabling synchronization from the other tactical planning problems, except the work of [12] that tried to minimize also the total number of required vehicles and the total deadheading time of all daily trips. This was achieved by solving each objective separately, using bi-level programming where the number of the required vehicles was solved first and the total transfer time of passengers was minimized using a heuristic algorithm at the second stage.

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In this work we solve the network-wide synchronized scheduling (NSS) problem. We generate timetables that favor the synchronization among different bus lines in order to reduce the transfer waiting times while also improving the performance of each individual bus line (resulting in a multi-objective optimization problem).

In the above-mentioned literature, the stochastic nature of travel times and passenger demand was not taken into consideration. However, this is a very important aspect because the expected and the actual arrival times of buses at stops can differ significantly in real operations. For instance, [8] explored the waiting times of passengers at transfer stops in the case of rail synchronization and showed that synchronization has no effect in real operations if the arrival times at the transfer stops fluctuate significantly from the expected ones. [5] studied thoroughly the importance of stochasticity at the multi-line synchronization problem and is the most relevant prior work in this research domain.

In this work we consider the stochasticity factor in the travel times of daily trips while advancing beyond the work of [5] in the following key respects: (i) addresses the tactical (rather than real-time) synchronization problem (i.e., offline optimization of the dispatching times of the daily trips); (ii) minimizes the overall passenger waiting (both at the transfer stops and at the individual line level); (iii) factors in the required walking times between stops in close vicinity; (iv) considers vehicle capacity limits; and (v) considers regulatory constraints such as headway limits for successive bus trips to ensure an “almost” even distribution of trips across the day.

Problem formulation and solution approach

The synchronization of bus lines under uncertainty requires the simultaneous optimization of the dispatching times of trips that belong to different bus lines but intersect at common stops, enabling transfers. To provide a tangible example, if for two bus lines l_1 and l_2 with $N_1 = N_2 = 200$ daily trips each trip needs to be synchronized, the decision variables of this optimization problem are the 400 dispatching times of the trips that belong to these two lines.

The dispatching times of the daily trips of a bus line can be represented by a vector with integer values, $\mathbf{x} = \{x_1, \dots, x_n, \dots, x_N\}$, which denotes the dispatching times of all trips in minutes.

The bus synchronization problem is formulated as a multi-objective problem that minimizes the waiting times of passengers at transfer stops and at the same time minimizes the excess waiting times of passengers that use a single bus line for their trip. The two objectives can be combined into one objective function using a weight factor, W , for examining the trade-off between the excess waiting times of passengers that use only one bus line for their trip and the transfer waiting times. For instance, if EWT_1 and EWT_2 are the average excess waiting times of two bus lines l_1 and l_2 that intersect at some bus stops

and WT is the total waiting times of passengers at transfer stops, then the objective of the bus synchronization problem can be defined as:

$$\min_{\mathbf{x}_1, \mathbf{x}_2} \frac{1}{2} \left(EWT_1(\mathbf{x}_1) + EWT_2(\mathbf{x}_2) \right) + W \cdot WT(\mathbf{x}_1, \mathbf{x}_2) \quad (1)$$

where \mathbf{x}_1 and \mathbf{x}_2 are the dispatching times of all daily trips that belong to line l_1 and line l_2 respectively. $EWT_1(\mathbf{x}_1)$ and $EWT_2(\mathbf{x}_2)$ denote the excess waiting time of the passengers of line l_1 and l_2 respectively calculated based on the deviation of the actual passenger waiting times from the planned ones [9]. $WT(\mathbf{x}_1, \mathbf{x}_2)$ is the total waiting time of passengers at transfer stops in minutes.

Setting the dispatching times of bus trips (which are the decision variables of the timetabling synchronization problem) is a discrete, multi-variate optimization problem for which it is not possible to find an exact solution in practice.

Model implementation and application

Given the above, we apply several heuristic optimization methods for solving the NSS problem: (i) simulated annealing with linear cooling; (ii) a sequential genetic algorithm; (iii) branch and bound and (iv) sequential hill climbing for minimizing the multi-objective optimization problem. In figure 2 we plot the results of coordinating two bus lines that intersect at several bus stops. In the plot we present the *total* transfer waiting times of passengers during the day, $WT(\mathbf{x}_1, \mathbf{x}_2)$, in minutes and the *average* excess waiting times, $EWT = \frac{1}{2} \left(EWT_1(\mathbf{x}_1) + EWT_2(\mathbf{x}_2) \right)$, of passengers of both bus services in minutes. The two examined bus lines are lines 1 and 4 in Stockholm that intersect at five (5) bus stops (table 1 summarizes the general characteristics of the two bus lines and figure 1 displays the locations of the bus stops). The two bus lines are bi-directional.

Table 1 General characteristics of bus lines 1 and 4 in Stockholm

Bus line	Direction	Bus stops	Daily trips	Dispatching time of first trip	Dispatching time of last trip	Average dispatching headway
1	eastbound	32	169	05:00	00:35	7.164 min
1	westbound	31	162	05:23	00:35	7.217 min
4	northbound	31	197	05:02	00:46	6.051 min
4	southbound	30	203	05:00	00:45	5.871 min

The performance of the four heuristic optimization algorithms in terms of convergence and computational costs are presented in table 2. The tests are implemented on a 2556MHz processor machine with 1024MB RAM. From table 2 one can notice that the sequential hill climbing algorithm had the best



Fig. 1 Transfer stops between bus line 1 and bus line 4 in Stockholm (source: Google maps)

performance on minimizing the objective function and its computation time was only 27 minutes. The simulated annealing method was even faster than the sequential hill climbing, but had the worst performance compared to the other methods.

Table 2 Summary results comparing the minimization of the multi-objective function and the computational costs of the heuristic search methods

	Objective function value (unitless)	Computation time (min)
Initial scenario (do-nothing)	30.18	-
Simulated Annealing	17.72	16
Genetic Algorithm	5.72	187
Branch and Bound	2.219	4132
Seq. Hill-climbing	2.216	27

Before analyzing the results of figure 2, we should first note that the waiting times of passengers, WT , express the total waiting times at the five transfer stops in minutes during the entire day. If one wishes to derive the average transfer waiting time the value of WT should be divided by the total number of daily transfers at all transfer stops. From figure 2 one can note that the regularity of the individual bus lines which is expressed by the exceeding waiting times of passengers at stops is sacrificed when reducing the transfer waiting times and vice versa. Hence, the main challenge is to establish an optimal

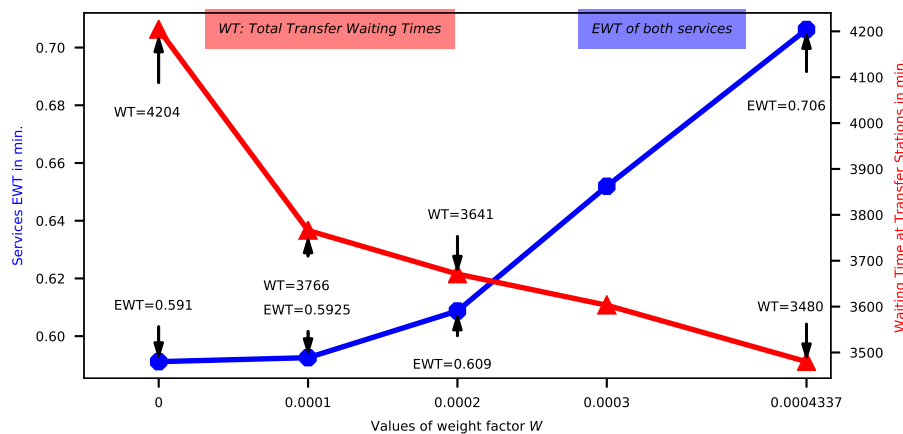


Fig. 2 Optimization of the regularity-based bus coordination problem for different values of weight factor W showcasing the trade-off between service regularity and passengers waiting times at transfer stations

trade-off between the excess waiting times of passengers that use only one bus line for their travel and the transfer waiting times of passengers that use at least two bus lines before reaching their destination.

Conclusions and outlook

In conclusion, this study examines the synchronization potential of different bus lines during the tactical planning phase. The main finding is that there can be an advantageous trade-off between the excess waiting times of regular passengers and the waiting times of passengers at transfer stops (i.e., from figure 2 it is evident that for 2.8% deterioration in the EWT of passengers, the total transfer waiting times are reduced by 12.77%). The desirable trade-off will be established in an on-going work based on passenger flow distributions. In future research the study will be expanded to the entire bus network of Stockholm for improving further the robustness of the optimized timetables to variations in travel times and passenger demand patterns.

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