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Cats, Oded; Gkiotsalitis, K.

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Network-wide synchronized scheduling of public transport services

Konstantinos Gkiotsalitis · Oded Cats

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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.

Dr. K. Gkiotsalitis
NEC Laboratories Europe, Kuerfuersten-Anlage 36, 69115 Heidelberg, Germany
E-mail: konstantinos.gkiotsalitis@neclab.eu

Dr. O. Cats
Delft University of Technology, Postbus 5, 2600 AA Delft, The Netherlands
E-mail: o.cats@tudelft.nl
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 trips 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, $x = \{x_1, ..., x_n, ..., x_N\}$, 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:

\[
\min_{x_1, x_2} \frac{1}{2} \left( EWT_1(x_1) + EWT_2(x_2) \right) + W \cdot WT(x_1, x_2)
\]

where \( x_1 \) and \( x_2 \) are the dispatching times of all daily trips that belong to line \( l_1 \) and line \( l_2 \) respectively. \( EWT_1(x_1) \) and \( EWT_2(x_2) \) 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]. \( WT(x_1, x_2) \) 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, \( WT(x_1, x_2) \), in minutes and the average excess waiting times, \( EWT = \frac{1}{2} \left( EWT_1(x_1) + EWT_2(x_2) \right) \), 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>
<thead>
<tr>
<th>Bus line</th>
<th>Direction</th>
<th>Bus stops</th>
<th>Daily trips</th>
<th>Dispatching time of first trip</th>
<th>Dispatching time of last trip</th>
<th>Average dispatching headway</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>eastbound</td>
<td>32</td>
<td>169</td>
<td>05:00</td>
<td>00:35</td>
<td>7.164 min</td>
</tr>
<tr>
<td>1</td>
<td>westbound</td>
<td>31</td>
<td>162</td>
<td>05:23</td>
<td>00:35</td>
<td>7.217 min</td>
</tr>
<tr>
<td>4</td>
<td>northbound</td>
<td>31</td>
<td>197</td>
<td>05:02</td>
<td>00:46</td>
<td>6.051 min</td>
</tr>
<tr>
<td>4</td>
<td>southbound</td>
<td>30</td>
<td>203</td>
<td>05:00</td>
<td>00:45</td>
<td>5.871 min</td>
</tr>
</tbody>
</table>

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
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性能在最小化目标函数和其计算时间时的性能仅为27分钟。模拟退火方法甚至比顺序爬坡更快，但与其他方法相比，其性能最差。

表2 比较多目标函数的最小化和启发式搜索方法的计算成本

<table>
<thead>
<tr>
<th></th>
<th>目标函数值 (无量纲)</th>
<th>计算时间 (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>初始方案 (无操作)</td>
<td>30.18</td>
<td>-</td>
</tr>
<tr>
<td>模拟退火</td>
<td>17.72</td>
<td>16</td>
</tr>
<tr>
<td>遗传算法</td>
<td>5.72</td>
<td>187</td>
</tr>
<tr>
<td>分支与定界</td>
<td>2.219</td>
<td>4132</td>
</tr>
<tr>
<td>顺序爬坡</td>
<td>2.216</td>
<td>27</td>
</tr>
</tbody>
</table>

在分析图2的结果之前，我们首先应该注意，乘客的等待时间，\(WT\)，表示全天五个换乘站的总等待时间，以分钟为单位。如果要推算平均换乘等待时间，\(WT\)的值应该除以全日的总换乘次数。从图2中可以看出，通过减少换乘等待时间而牺牲掉的单条线路的规律性，与通过增加换乘等待时间而提高的单条线路的规律性是相辅相成的。因此，主要的挑战是建立一个最优的
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.

References