SCHEDULE SYNCHRONIZATION IN PUBLIC TRANSPORT BY TABU SEARCH AND GENETIC METHOD

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1. Introduction

The transfers importance in provision of public transport service is motivated by several operational reasons. The transfers necessity results from the self-evident fact that especially due to econimic reasons it is impossible to cover all origin-destination passenger demands by direct connections. This is why, a transit network can only have a specified density of such connections determined first of all by a given demand structure. This visualize an intramodal (e.g. bus network) and intermodal (e.g. metro with bus network) transfers integration capabilities in the transit networks. Moreover, by transfers it is possible advantageously influence of the transit network service characteristics: increase of possible number of travel paths, improvement of transit network operational flexibility and efficiency (by adjustment of each line parameters to its functional and physical conditions, volume and character of demand) concentration of the passenger flows on the main routes equipped with better vehicles and transportation infrastructure which guarantee high service quality and efficient resource utilization. Unfortunately, transfers involve certain inconveniences connected with discomfort of boarding a new vehicle (necessity of passenger orientation and walking between vehicles on feeder and receiving lines), negative perception of waiting for arrival new vehicle and existence of some delay during a trip. The elimination of these inconveniences by schedule synchronization to provide an attractive service level with easy access and transfer possibilities, is continuously a challenging problem in timetable construction. A major shortage of the previous researches concerning the transfer synchronization is that they disregard of the dispatching control actions (i.e. the bottom layer in the hierarchical management and control system [2,3,8]) whose main purpose is the stabilization of the bus trajectories (punctuality control) or headways (regularity control) around schedule trajectories / headways, and consequent counteraction to the random off-schedule deviations [1-3,7]. Therefore, it seems sensible to classify the transfer optimization tools into schedule related (time buffers / layovers, optimization of departures from terminals, service frequency adjustments) and dispatching control related (synchronizing dispatching control). The addition of layovers (timed transfers) increase transfer reliability by means of time redundancy (i.e. assignment of time compensatory buffers to absorb of service randomness) [19-21]. This however implies higher operating costs and unnecessary delays for through-passengers, therefore it was argued that timed transfers are inappropriate for large transit networks with decentralized transfers [13][9]. Some analytical attempts have been made to optimize layovers at the transfer points for simple deterministic and simulation models [20]. Motivated by the fact that service randomness should be compensated at the origin, the problem of optimal distribution of layovers along the routes was presented in [3]. This approach mitigate to high degree the disadvantages of timed transfers. The efficiency of transfers synchronization by selection of buses departure times from terminals, which minimize network disutility functions measuring the overall transfers inconvenience, essentially depends on the representative features of these functions [6][9-17][20][22]. Most approaches used the global waiting time disutility funnction under deterministic travel times assumption [11,14-17,22]. The simulation model with stochastic travel times representation and a wide range of objective functions was presented in [9] and closed form analytical solutions for this approach in [5,6]. The dispatching synchronizing control problems and solutions were presented in [1-7]. The headway harmonization problems i.e. synchronization different transit lines on a common segment of routes, were considered in [18][22] and some analytical solutions were presented in [5,6]. In this paper two schedule synchronization problems in public transit network are formulated and solved. The first one is concerned with a transfer synchronization when passengers changing transit lines at transfer points, whereas the second with harmonization of headways. This paper is organized as follows: Section 2 is devoted to issues of representation and formulation of the synchronization problems. In Section 3, the transfer synchronization problems are formulated and investigated. Problem of synchronization different lines on a common segment of routes is discussed in Section 4. Finally, the validity and practicality of the proposed approaches are demonstrated by real-life examples in Section 5.

2. ISSUES OF PROBLEMS REPRESENTATION AND FORMULATION

Network optimization problems have usually low legibility due to lack of unification approach an issue of problem representation and formulation. To facilitate the problem representation the following standard description of the public transport system (lines) by a sequence of problem assumptions and specifications is proposed: **[5]**

1. General Process Features (GPF)

- working conditions: steady-state (**s - s**), dynamical (**d - s**)
- **S**tochastic / **D**eterministic representation (S / D)
- **L**inear / **N**on**L**inear models (**L** / **NL**)
- general process characteristics: isotropy (**iso**) / anisotropy (**aniso**)

2. Demand (DMD)

- **Origin -Destination trips pattern**: **D**emand **F**unctions (**DF**) : fixed (**f**), variable (**v**)
- **Passenger Arrival Pattern** (**PAP**):
  * Random (**RAP**)**,** Coincidential (**CAP**), Timed (**TAP**), mixed (**RTAP**) passenger arrivals
- **Passenger Behavioural Aspects (PBA):**
  * **T**rip **P**references (**TP**): fixed (**f**) , variable (**v**)
  ⇒ Mode and Route choices : direct (d), with "n" transfers (tr^n) ; Starting/transfer/destination stops
  * **P**assenger **R**esponses (**PR**) to offered service quality:
  independent (**i**); correlated (**c**); given pattern (**p**).

3. Supply (Transportation System) (SUP)

- **Network structure G = < N**odes**, L**inks **>: < N , L >**
- **Network Configuration** (**NC**): radial (**rd**) ; rectangular (**r**)
- **Node** specifications: service frequency ($\mathbf{f_N}$)/headways ($\mathbf{H_N}$), Transfer times (**T**r) and passenger flows ($\mathbf{q_{Tr}}$)
- **Link** specifications: service frequency ($\mathbf{f_L}$) / headways ($\mathbf{H_L}$), running times ($\mathbf{T_L}$), passenger flows (q_L)
- **General Route Parameters (RP)**
  * Llayout type: [**length** (short (**s**), medium (**m**), lomg (**l**);
  * Number (**n**) and type (i.e. Single (**SRS**) or Multiple (**MRS**)) of route stops
  * Terminals (**T**)/ Transfer stops (**Trs**)
- **Timetable (Schedule)** (**SCH**)
  * service frequency ($\mathbf{f_p/f_{off}}$) / headways ($\mathbf{H_p/H_{off}}$) in the peak and of peak periods
  * Vehicle stop regime: all stops (**a-s**); on call stopping (**c-s**); demand stopping (**d-s**)
  * Scheduled time buffers (**BT**) at terminals (T) and timing points TP.
  * Scheduled arrival/departure times for T and TP
- **Vehicles (VEH):**
  * Fleet type (homogeneous (**h**) **;** non-homogeneous (**n-h**)
  * Number of vehicles (**m**)
  * Bus (Vehicle) Capacity **(BCA):** unlimited (**UBCA**)**,** limited (**LBCA**)

4. Operation:

- **Passengers Service Process (PSP):**
  * service process is **: disregarded** (**0**), **dominated by boarding / alighting** passengers (**B / A**), by **both streams** of passengers (**BA**)
  * number of boarding ($\mathbf{n^B}$), / alighting ($\mathbf{n^A}$) passengers are correlated in time and /or space (**c**)
- **Vehicle Arrival Pattern (VAP):**
  * Vehicle headways / arrival times distributions **(HD / TD):**
  * **deterministic** (**d**); **random** (**r**): markovian (Poisson) (**M**), normal (**N**), arbitrary (**G**), binomial (**B**)
  * identical (**i.d**), identical and independent (**i.i.d**), correlated (**c**) distributions

For example the representation of a transfer optimization problem presented in [11,14,22] may be described in terms of proposed specifications as follows:Problem Representation: GPF[s-s,D,iso]; DMD[Dff,PBA(Tpf ,Pri)];

SUP[<Transfer Nodes (TN) , Transfer Connections (TC)> , TN(f_N/H_N, Tr, q_{Tr}), TC (f_{TC}/H_{TC}), RP (T/Tr), VEH(h, UVCA) , SCHD (f/H, BT), VAP (d)]. This means: The general steady-state, isotropic and deterministic approach to representation of the plant processes with the fixed passenger demand and trip preferences independent of the offered service. The network structure consist of transfer nodes and transfer connections with specified transfer: frequencies, times and passenger flows for transfer nodes and service frequencies and running times for transfer connections. The routes are represented by terminals and transfer stops and are working with homogeneous fleet of vehicles having unlimited capacity. The schedule specifications are fixed and known as well as deterministic vehicle arrival patterns.

To facilitate the formulation of the optimization problems for a given problem representation the following standard notation is proposed: **P $_{\min}$ u Q | Ω** where the sequence gives the following item specifications of optimization problems:

P. Scalar **(PO)** or Multicriterial **(MOP)**optimization problem. In the last case the criterion space ($Y,\overset{<}{}D$) is partially ordered by a strictly positive convex cone D. This makes it possible to find in a given set $Q(\Omega)\subset Y$ of admissible performance its D-minimal element q=Q(u) which fulfils the condition $(q-D)\cap Q(\Omega)=\phi$ called the polyoptimal performance and correspondingly the control element $u\in\Omega$ called the polyoptimal solution.

u. Vector of decision variables

Q. Criterion function **Q:Ω→ Y** where **Y** is a linear space called the criterion space

Ω-. Set of admissible decision variables in the decision space U

For example the formulation of a QSAP transfer optimization problem presented in [11,14,22] may be stated as follows: For a given sets of lines L={1,..,m} and possible vehicle departure times from terminals DT={1,..,n} (determined for each line $i\in L$) and cost matrix $\{c_{ihjk}\}$ representing total transfers waiting times resulted from assigment (by means of binary variables x_{ih}) exactly one departure time to each line;

$$PO_{\min} \quad x \quad Q(x) = \sum_{i,j=1}^{m} \sum_{h,k=1}^{n} c_{ihjk} x_{ih} x_{jk} \quad \| \ \Omega = \left\{ x : \sum_{h=1}^{n} x_{ih} = 1, \ x_{ih} \in \{0,1\} \right\} \qquad (1)$$

2. TRANSFERS SYNCHRONIZATION IN A TRANSIT NETWORK

For solving transfers optimization problem we refer to QSAP (Quadratic Semi-Assignment Problem) formulation presented in [11, 14, 22] (see problem formulation (1)). In this paper we propose to extend the set of transfer points to a set of synchronizing points (i.e. the first bus stops on a common segments of routes) with associated headways harmonization costs $\{c^*_{ihjk}=\sum(H_{ihjk}-H^*)^2\}$ depending on vehicle departure times from terminals and representing off-perfect harmonization headways deviations Q*(x). The modified problem may be formulated similarly as in (1) with $Z(x)=\lambda Q(x) + (1-\lambda)\ Q^*(x);\ \lambda\in[0,1]$ as criterion function. Due to high complexity the QSAP real world problems may be only solved by heuristic approaches e.g. Tabu Search strategy which was used in [11,22]. In paper we propose an integrated of Tabu Search and Genetic solution method in which the starting point is generated by regret heuristic [14] and CSM [22] connected with several genetic mutation and crossing operators. The efficiency of this method is illustrated by numerical example in section 5.

3. SYNCHRONIZATION OF DIFFERENT LINES ON A COMMON SEGMENT OF ROUTES

The common segments of different lines usually occur on the main routes of the public transport service i.e. routes with high passengers flows and service realized with high and medium frequency. Moreover, on these lines usually dispatching control actions are realized with the aim of stabilization of the current schedules. In general the scheduled headways on various lines are different, but for a given time period during a day (e.g. for a rush-hour) they are fixed on individual lines. In such situation the following problem representation for headways harmonization seems to be reasonable:

GPF [*s-s, S, iso*]; **DMD** [*Dfv, RAP,PBA* (*Tpv, PRc*)]; **SUP**[<Common Segment Stops (*CSS*), Common Segment Links (*CS*L)>, *CSS* (H_{CSS}), *CS*L (H_{CSL}, T_{CSL}), *RP* (T/CSS), *VEH*(h, LVCA) , *SCHD* (f/H, BT,TP/T), *VAP* (i.i.d)].

Remarks:

1. The dispatching control efficiency determine to a high degree the significance of the random components in the realization of the scheduled service [2,7,8]. In particular, the purpose of dispatching control with respect to synchronizing point (i.e. the first bus stop on a common segment of routes) is the stabilization of the schedules synchronization **offset times** $\mathbf{t_0} = \{t_{0i}\ i=1,..,l\}$or their increments $\Delta\mathbf{t_0} = \{\Delta\mathbf{t_{0i}}=\mathbf{t_{oi}}-\mathbf{t_{0i-1}}\ i=1,..,l-1\}$ of

the bus arrivals from different lines to this synchonization point (see lines with headways H_1, H_2 and H_3 in Fig. 1 [6]).

2. Because the dynamical estimation of the share of passengers which use individual lines is practically unrealizable, whence we assume that the basic demands of passengers on a given line are fulfilled by proper selection of service frequency, whereas the main synchronization purpose is to minimize the waiting time trip inconveniences first of all for passengers which use common segments of routes. This is why the minimum of the passengers waiting time related measure, will be achieved by uniform bus arrivals from different lines at the stops on a common segment of routes.

To formulate optimal headways harmonization problem we assume for the common segment of routes the headways irregularity indices e.g. an integrated headways variance Var (H) or an absolute moment off-average headway H* deviations d(h)

$$Var(H) = \left\{\sum_{i=1}^{n} H_i^2 - nH^*\right\}/(n-1) \qquad ; d(h) = \sum_{i=1}^{n} \left| H_i - H^* \right| / n \qquad (2)$$

where $H^* = \sum H_i / n$ is an integrated average headway on a common segment of routes. As may be seen the harmonization of scheduled headways do not influence the number of buses i.e. average headway H* then $Q_1(t_0) = \sum_{i=1}^{n} H_i^2(t_0)/(n-1)$ and $Q_2(t_0) = d(t_0)$ indices may be used as harmonization criteria and harmonization problem may be stated as follows:

$$PO_{\min} \quad t_0 \quad Q(t_0) \;\Big|\; t_0 \in [0,H] \;; t_0 = [t_{01}, t_{02}, .., t_{0l}]^T ; H = [H_1, H_2, .., H_l]^T \qquad (3)$$

Remarks:

1. The general analytical solutions of this problem for one common segment of routes with rational (commensurate, multiple, equal) headways were presented in [5,6].

2. In the case of equal headways on individual lines (i=1,..,l) the optimal solution of this harmonization problem with $Q_1(t_0)=\Delta t_0^T \Delta t_0 + (H-e^T\Delta t_0)^T(H-e^T\Delta t_0)$ (where vector e has all elements equal to 1) has (intiitive evident) form $\Delta t_0 = H^* e$ due to $Q_1(t_0)$ symmetry and may be derived formally: from $\partial Q_1(t_0)/\partial \Delta t_0=0$ we have $\Delta t_0=(I+ee^T)^{-1}eH$ and due to Woodbury's identity $(I+ee^T)^{-1}=I-ee^T/(1+e^Te)$ the solution equals to $\Delta t_0 = (H/l)\, e = H^*\, e$.

3. The harmonization problem (3) may be extended to multiple common segments of routes (i.e. harmonization zones $z \in Z$, Fig. 2) by modification of $Q_1(t_0) = \sum_{i=1}^{n} [H_i(t_0) - H^*]^2/(n-1)$ and summation over the $z \in Z$. Practically this may be realized for example in bilevel structure (see Fig. 2). The illustrative real-life example is presented in section 5.

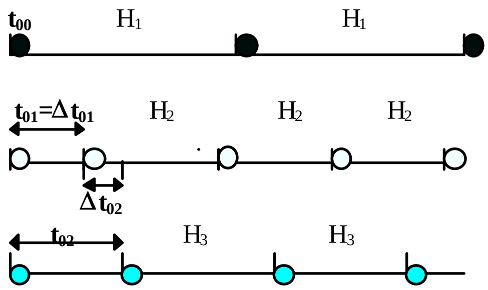

Fig. 1 The schedules synchronization offset times $\{t_{0i}\}$.

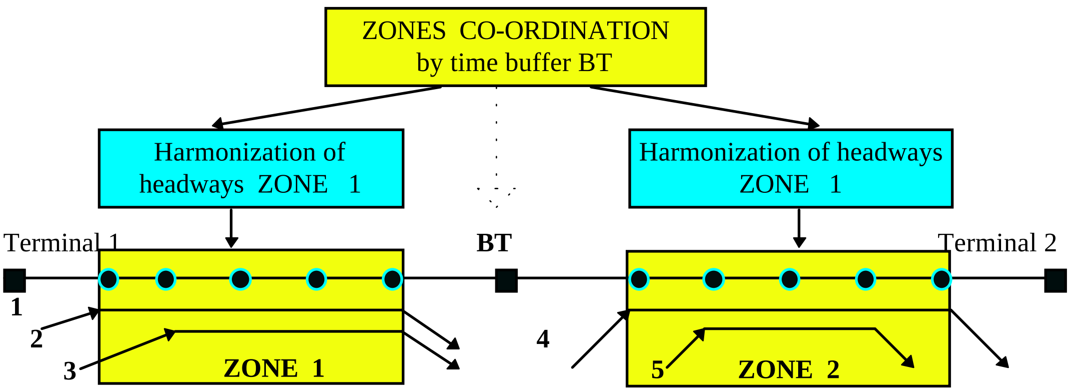

Fig. 2. Headways harmonization idea in the case of multiple zones

5. NUMERICAL EXAMPLES

Example 1:

We consider 9 tram lines in Cracow (see Fig. 3) which are working with a common headway of 15(min). The set of departure times from terminals DT [illegible] possible values i.e. {[illegible]min).

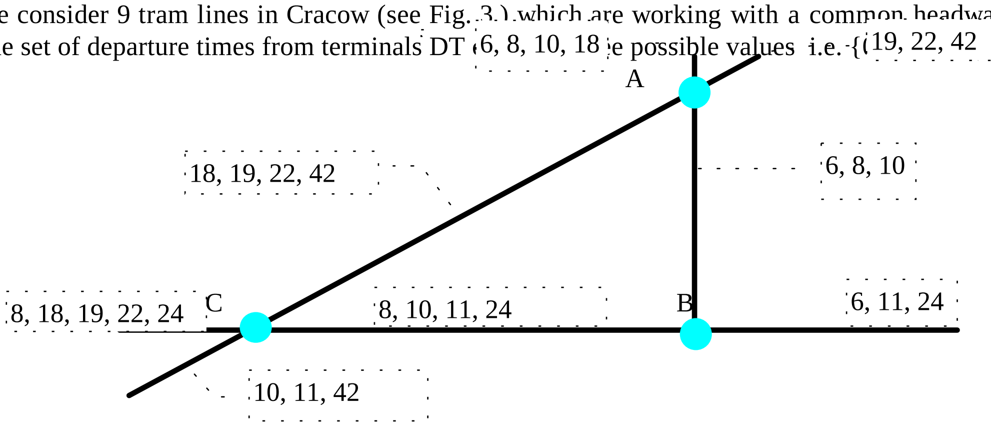

Fig. 3. Scheme of the tram lines in example 1

Results:

Best solution	Number of iterations	Population	Optimal value of criterion
1,2,2,3,2,1,2,1,1	10	100	74
1,2,1,1,3,3,2,3,3	10	200	96
1,2,1,1,3,3,2,3,3	20	300	71
1,2,3,1,2,2,3,2,2	20	500	69

Example 2.

We consider three zones of the tram network in Cracow which are working with a common headway of 15(min): Zone 1 { lines no. 24, 3, 9, 43}; Zone 2 { lines no. 24, 3, 9, 43, 6 13}; Zone 3 { lines no. 24, 6}. The average headways for perfect headways harmonization in zones are equal respectively: H_1*=3.75(min);H_2*=2.5(min) and H_3*=7.5(min). The optimal offset times for each zone are equal respectively: Zone 1: Δt_{01} = [0, 3.75, 7.5, 11.25]; Zone 2: Δt_{02} = [0, 1.9, 3.75, 7.5, 9.3, 11.3];
Zone 3: Δt_{03}=[0, 9.3].

6. CONCLUSIONS

The high improvements of the transit service quality may be obtained by intramodal and intermodal intergration of the service on the schedules synchronization way and complementary effective dispatching control actions. The progress in hardware capabilities and development of computer-aided network optimization tools create a necessary conditions for such improvements. In the paper the practical efficiency of the intergrated Tabu Search and Genetic approach is demonstrated by real-life examples of tram lines from Cracow public transport network.

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