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Optimal Mode of Interaction between Rail and Ground Urban Passenger Transport within the TIH

Sergey P. VAKULENKO

Nadezhda Yu. EVREENOVA

Kirill A. KALININ

***Sergey P. Vakulenko*[1]*, Nadezhda Yu. Evreenova*[2]*, Kirill A. Kalinin*[3]**
[1, 2, 3] *Russian University of Transport, Moscow, Russia.*
✉ [2] *nevreenova@mail.ru.*

ABSTRACT

The development of the infrastructure of transport interchange hubs is currently necessary to meet the growing demand for passenger services and to prevent infrastructural constraints on technological modernisation of entire transport system. Large-scale infrastructure projects are of a pronounced complex nature, involving many related industries in their sphere, which ultimately leads to an additional increase in GDP. A modern transport interchange hub is a public and business centre that ensures the quality of services, safety, technological reliability and creates an active business environment based on development of passenger infrastructure. Considering the latest global trends in the field of passenger transportation that englobe multimodality, speed, comfort and safety of passenger transportation, there is a pronounced need to develop modern transport interchange hubs.

Minimisation of passenger transfer time between interacting modes of transport at TIH can be achieved by coordinating contact timetables of different modes of transport. To do this, it is necessary first, to solve the problem of determining the optimal mode of interaction between ground urban passenger and rail transport.

The objective of the study described in the article is to determine the mode of supply of the units of ground urban passenger transport, which ensures the minimum time for a passenger to stay at TIH in accordance with the timetable of electric trains regarding the considered TIH. To reduce the dimension of the problem, it is assumed that all electric trains will have the same composition.

The methods of scheduling theory were used to solve the problem in the context of the study that resulted in a formalised problem of determining the optimal mode of interaction between ground urban passenger transport in transport interchange hubs illustrated by the example of interaction of rail and urban road transport and considering all existing constraints.

Keywords: interaction of modes of transport, scheduling theory, ground urban passenger transport, transport interchange hub, rail transport.

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INTRODUCTION

The infrastructure of the transport interchange hub (TIH) is an important part of national passenger system [1]. TIH as the most important element of the transport infrastructure, providing passenger transportation, is of great socio-economic importance [2–4]. Modern TIH can and should be considered as a point of growth of social and business activity of the population. The international practices of TIH have contributed to cumulate a wealth of experience in creating multifunctional public and business facilities [5–7]. We see examples of such TIHs in Europe, Asian countries, and the USA.

A significant aspect of improving the quality of passenger service in TIH is minimisation of the passenger transfer time between interacting modes of transport [8], which can be achieved by coordinating contact timetables for different modes of transport. First, it is necessary to solve the problem of determining the optimal mode of interaction between ground urban passenger transport (GUPT) and rail transport [9; 10] using the methods of scheduling theory [11–13].

STATEMENT OF RESEARCH OBJECTIVE

Let us formulate the problem of determining the optimal mode of interaction between modes of transport in TIH using the example of interaction of rail transport and GUPT (buses, trolleybuses, trams, fixed-route taxis (jitneys), taxis, personal vehicles).

Electric trains arrive at TIH with passengers changing to GUPT with further destination at $n \in [1...N]$ points, while the location of the considered TIH is denoted by $n_0 = 0$. Passengers arrive at TIH from each of these points to transfer to the electric train. The capacity and parameters of the considered TIH, the number of urban transport routes interacting in the TIH, the composition of electric trains for various purposes are known.

The *objective* of the study is to determine the mode of supply of vehicles of urban passenger transport, which ensures the minimum time for a passenger to stay at TIH during the planning period $t \in [1...T]$, divided by ϑ_{max} equal intervals, in accordance with the established mode of traffic (timetable) of electric trains for the considered TIH.

RESULTS

Mathematical Formulation of the Problem

To formalise the problem, we describe the operation of each mode of transport and of the TIH in the form of a system of constraints.

The Operation of Rail Transport

Let there be a characteristic of the selected time periods $pt_1, pt_2, ... pt_\vartheta, ... pt_{\vartheta max}, pt \in N$, where the length of the characterised period depends on the discretisation value of the problem, each of which is a reduced estimate of T/ϑ, min, of the considered period of TIH operation. Each pt_ϑ is characterised by the moment of the beginning of the interval t_i^ϑ and by the moment of its end t_{i+1}^ϑ.

To reduce the dimension of the problem, we assume that all electric trains will have the same composition [14–16], then the maximum number of passengers that can arrive by an electric train will be denoted by g, the time of boarding and disembarking from the electric train will be τ. As an additional constraint, we accept that boarding an electric train of one and the same destination can only begin after passengers have disembarked from it [17–19].

We formulate these constraints as follows: $0 \le t_i^\vartheta < t_{i+1}^\vartheta \le T$, $\left(t_{i+1}^\vartheta - t_i^\vartheta\right) \ge 2\tau$.

GUPT Operation

Let us use the following designations: τ_n – the travel time of a vehicle of urban passenger transport towards point n, min; as $s \in [1...S]$ – the total number of the units of rolling stock of urban passenger transport going to point n during the period T under consideration; $\tau_{g_{bus}n}^s$ – time of boarding/disembarking for GUPT at point n; $Q\left(t_i^\vartheta\right) = \left\{q_n\left(t_i^\vartheta\right)\right\}$ $n \in \overline{1,N}$ – the vector of presence of passengers to be delivered to TIH; $q_n\left(t_i^\vartheta\right) = 1$, if there are passengers at point n who can be delivered to TIH at time t_i^ϑ and $q_n\left(t_i^\vartheta\right) = 0$ otherwise; M_n^s – the maximum number of GUPT vehicles' (s) journeys from TIH to point n; P – TIH's transit capacity to process GUPT vehicles. Urban transport vehicles going to point n have different capacity h_n^s.

Let's create a system of constraints that describes the transport process using Boolean variables:

$$\overline{U_{0n}^{sm_n^s}}(t_i^\vartheta) = \begin{cases} \textit{1, if at the moment } t^\vartheta_i \textit{ an urban transport vehicle s during } m^s_n \textit{ journey} \\ \textit{moves with passengers from TIH to the point n;} \\ \textit{0 otherwise.} \end{cases} \quad (1)$$

$$U_{0n}^{sm_n^s}(t_i^{\vartheta}) = \begin{cases} \text{1, if at the moment } t_i^{\vartheta} \text{ an urban transport vehicle } s \text{ during } m_n^s \text{ journey} \\ \text{moves without passengers from TIH to the point } n; \\ \text{0 otherwise.} \end{cases} \quad (2)$$

$$\overline{U_{n0}^{sm_0^s}}(t_i^{\vartheta}) = \begin{cases} \text{1, if at the moment } t_i^{\vartheta} \text{ an urban transport vehicle } s \text{ during } m_0^s \text{ journey} \\ \text{moves with passengers to TIH from the point } n; \\ \text{0 otherwise.} \end{cases} \quad (3)$$

$$U_{n0}^{sm_0^s}(t_i^{\vartheta}) = \begin{cases} \text{1, if at the moment } t_i^{\vartheta} \text{ an urban transport vehicle } s \text{ during } m_0^s \text{ journey} \\ \text{moves without passengers to TIH from the point } n; \\ \text{0 otherwise.} \end{cases} \quad (4)$$

$$V_{0n}^{sm_n^s}(t_i^{\vartheta}) = \overline{U_{0n}^{sm_n^s}}(t_i^{\vartheta}) + U_{0n}^{sm_n^s}(t_i^{\vartheta}); \quad (5)$$

$$V_{n0}^{sm_0^s}(t_i^{\vartheta}) = \overline{U_{n0}^{sm_0^s}}(t_i^{\vartheta}) + U_{n0}^{sm_0^s}(t_i^{\vartheta}); \quad (6)$$

$$\overline{Z_{n}^{sm_n^s}}(t_i^{\vartheta}) = \begin{cases} \text{1, if at the moment } t_i^{\vartheta} \text{ an urban transport vehicle } s \text{ after } m_n^s \text{ journey} \\ \text{is under embarkation at the point } n; \\ \text{0 otherwise.} \end{cases} \quad (7)$$

$$Z_{n}^{sm_n^s}(t_i^{\vartheta}) = \begin{cases} \text{1, if at the moment } t_i^{\vartheta} \text{ an urban transport vehicle } s \text{ after } m_n^s \text{ journey} \\ \text{is under disembarkation at the point } n; \\ \text{0 otherwise.} \end{cases} \quad (8)$$

$$\overline{Z_{0}^{sm_0^s}}(t_i^{\vartheta}) = \begin{cases} \text{1, if at the moment } t_i^{\vartheta} \text{ an urban transport vehicle } s \text{ after } m_n^s \text{ journey} \\ \text{is under disembarkation at TIH;} \\ \text{0 otherwise.} \end{cases} \quad (9)$$

$$Z_{0}^{sm_0^s}(t_i^{\vartheta}) = \begin{cases} \text{1, if at the moment } t_i^{\vartheta} \text{ an urban transport vehicle } s \text{ after } m_n^s \text{ journey} \\ \text{is under disembarkation at TIH;} \\ \text{0 otherwise.} \end{cases} \quad (10)$$

$$W_{n}^{sm_n^s}(t_i^{\vartheta}) = \overline{Z_{n}^{sm_n^s}}(t_i^{\vartheta}) + Z_{n}^{sm_n^s}(t_i^{\vartheta}); \quad (11)$$

$$W_{0}^{sm_0^s}(t_i^{\vartheta}) = \overline{Z_{0}^{sm_0^s}}(t_i^{\vartheta}) + Z_{0}^{sm_0^s}(t_i^{\vartheta}). \quad (12)$$

At any moment t_i^{ϑ} during the interval $pt\vartheta$ under consideration, any vehicle s can only be in one of the following eight states: in motion from TIH to point n making a journey m_n^s with or without passengers; in motion from point n to TIH making a journey m_0^s with and without passengers; at TIH after journey m_0^s under embarkation and under disembarkation; at point n after journey m_n^s under embarkation and under disembarkation.

For each type of GUPT, at any two consecutive times $t_i^{\vartheta}, t_{i+1}^{\vartheta} \in \overline{1,T}$, only one of eight situations occurs when moving along the connected route at the time:

- t_i^{ϑ} and t_{i+1}^{ϑ}: a vehicle moves to the point n from TIH.
- t_i^{ϑ} and t_{i+1}^{ϑ}: a vehicle moves from the point n to TIH.
- t_i^{ϑ}: a GUPT vehicle moves to the point n from TIH and at the moment t_{i+1}^{ϑ} it is at the point n.
- t_i^{ϑ}: a GUPT vehicle moves to TIH from the point n and at the moment t_{i+1}^{ϑ} it is at TIH.
- t_i^{ϑ} and t_{i+1}^{ϑ}: a GUPT vehicle is at the point n.
- t_i^{ϑ} and t_{i+1}^{ϑ}: a vehicle is at TIH.
- t_i^{ϑ}: a GUPT vehicle is at the point n and at the moment t_{i+1}^{ϑ} it moves to TIH.
- t_i^{ϑ}: a GUPT vehicle is at TIH and at the moment t_{i+1}^{ϑ} it moves to the point n.

For a GUPT vehicle s to be in only one of eight listed situations at every two successive moments t_i^{ϑ} and t^{ϑ}, the following constraints are necessary and sufficient:

$$\sum_{m_n^s=1}^{M_n^s} V_{0n}^{sm_n^s}\left(t_i^{\vartheta}\right) + \sum_{m_{n+k}^s=1}^{M_{n+k}^s} V_{0(n+k)}^{sm_{(n+k)}^s}\left(t_{i+1}^{\vartheta}\right) \le 1, \quad (13)$$

while $\forall s \in \overline{1,S}$, $\forall n \in \overline{1,N}$, $\forall\ t^\vartheta_i$, $t^\vartheta_{i+1} \in \overline{0,T}$,

where k is a variable characterising the difference in the serial number of the point n and all other points under consideration in the array ($k \neq n$; $k \in [1 - N; N - 1]$; $0 < n + k < N$; $k \in Z$).

These constraints prohibit the situation in which a vehicle s moves from TIH to two different points at two consecutive times.

Constraint

$$\sum_{m_n^s=1}^{M_n^s} V_{n0}^{sm_n^s}\left(t_i^\vartheta\right) + \sum_{m_{n+k}^s=1}^{M_{n+k}^s} V_{(n+k)0}^{sm_{(n+k)}^s}\left(t_{i+1}^\vartheta\right) \le 1\,, \qquad (14)$$

prohibits the situation in which a GUPT vehicle s moves to TIH from two different points at two consecutive times.

Constraint

$$\sum_{m_n^s=1}^{M_n^s} W_n^{sm_n^s}\left(t_i^\vartheta\right) + \sum_{\substack{k=1-N\\k\neq n}}^{N-1} \sum_{m_{n+k}^s=1}^{M_{n+k}^s} W_{n+k}^{sm_n^s}\left(t_{i+1}^\vartheta\right) \le 1\,, \qquad (15)$$

prohibits the situation in which a vehicle s at two consecutive times is at different points.

Constraints

$$\sum_{n=1}^{N}\sum_{m_n^s=1}^{M_n^s} V_{n0}^{sm_0^s}\left(t_i^\vartheta\right) + \sum_{\substack{k=1-N\\k\neq n}}^{N-1} \sum_{m_{n+k}^s=1}^{M_{n+k}^s} W_{n+k}^{sm_0^s}\left(t_{i+1}^\vartheta\right) \le 1\,, \qquad (16)$$

$$\sum_{n=1}^{N}\sum_{m_n^s=1}^{M_n^s} V_{0n}^{sm_n^s}\left(t_i^\vartheta\right) + \sum_{\substack{k=1-N\\k\neq n}}^{N-1} \sum_{m_{n+k}^s=1}^{M_{n+k}^s} W_{n+k}^{sm_n^s}\left(t_{i+1}^\vartheta\right) \le 1\,, \qquad (17)$$

prohibit the situation in which a GUPT vehicle s at the moment t^ϑ_i moves from the point n to TIH, and at the next moment t^ϑ_{i+1} is at the point $n+k$ and when at the moment t^ϑ_i moves from TIH to the point n, and at the moment t^ϑ_{i+1} is at the point $n+k$.

Constraints

$$\sum_{n=1}^{N}\sum_{m_n^s=1}^{M_n^s} \overline{U_{n0}^{sm_0^s}}\left(t_i^\vartheta\right) + \sum_{m_n^s=1}^{M_n^s} \overline{Z_n^{sm_n^s}}\left(t_i^\vartheta\right) \le 1\,; \qquad (18)$$

$$\sum_{n=1}^{N}\sum_{m_n^s=1}^{M_n^s} \overline{U_{0n}^{sm_n^s}}\left(t_i^\vartheta\right) + \sum_{m_n^s=1}^{M_n^s} \overline{Z_n^{sm_n^s}}\left(t_i^\vartheta\right) \le 1\,, \qquad (19)$$

prohibit the situation in which a GUPT vehicle s moves at the moment t^ϑ_i to the point n (to TIH) with passengers, and at the moment $t^\vartheta i+1$ is under embarkation at the point n (in TIH).

Constraints

$$\sum_{j=1}^{N}\left[V_{n0}^{sm_0^s}\left(t_i^\vartheta\right) + \sum_{m_{n+k}^s=1}^{M_{n+k}^s} V_{n0}^{sm_0^s}\left(t_{i+1}^\vartheta\right)\right] \le 1\,; \qquad (20)$$

$$\sum_{n=1}^{N}\left[V_{0n}^{sm_n^s}\left(t_i^\vartheta\right) + \sum_{m_{n+k}^s=1}^{M_{n+k}^s} V_{0n}^{sm_n^s}\left(t_{i+1}^\vartheta\right)\right] \le 1\,, \qquad (21)$$

prohibit the situation in which a GUPT vehicle s at two consecutive moments makes different journeys from TIH to any of the points.

Constraint

$$\sum_{n=1}^{N}\left[W_n^{sm_n^s}\left(t_i^\vartheta\right) + \sum_{m_{n+k}^s=1}^{M_{n+k}^s} W_n^{sm_n^s}\left(t_{i+1}^\vartheta\right)\right] \le 1\,, \qquad (22)$$

prohibits the situation, in which an urban passenger transport vehicle s at two consecutive moments is (after different journeys) at any point.

At each moment $t^\vartheta{}_i \in \overline{0,T}$ the number of GUPT vehicles, being at TIH, should not exceed its capacity to process GUPT vehicles:

$$\sum_{s=1}^{S}\sum_{m_n^s=1}^{M_n^s} W_0^{sm_0^s}\left(t_i^\vartheta\right) \le P\,. \qquad (23)$$

The condition for transporting passengers prohibits the situation when a GUPT vehicle leaves the point n with passengers at the moment $t^\vartheta{}_{i+1}$, and at the previous moment at the point n there were no passengers to be taken to TIH.

This condition is written as:

$$\sum_{m_n^s=1}^{M_n^s} \overline{Z_n^{sm_n^s}}\left(t_i^\vartheta\right) + \sum_{m_n^s=1}^{M_n^s} \overline{U_{n0}^{sm_0^s}}\left(t_{i+1}^\vartheta\right) \le 1, \qquad (24)$$

$\forall\ t_i^\vartheta$, n, $q_n\left(t_i^\vartheta\right) = 0$.

Initial and final conditions are set by fixing all variables:

$V_{0n}^{sm_n^s}(0), V_{0n}^{sm_n^s}(T), U_{0j}^{Sp_{0j}^s}(0), U_{0j}^{Sp_{0j}^s}(T);$

$W_n^{sm_n^s}(0), W_n^{sm_n^s}(T), W_0^{sm_n^s}(0), W_0^{sm_n^s}(T).$

TIH Operation

Let us introduce the following designations: $\Omega(t^\vartheta_i)$ – the number of passengers being at TIH at the moment t^ϑ_i; Ω_0 – the number of passengers being at TIH by the moment $t = 0$; g – the maximum number of passengers who can arrive with an electric train; h_s – the maximum number of passengers who can be transported by urban transport s; Ω_{max} – the maximum number of passengers who can be simultaneously at TIH.

The following ratios are to be met:

$$\Omega\left(t_i^\vartheta\right) \le \Omega_{max}\ \ \forall\ \ t_i^\vartheta\ \in [0, \mathrm{T}], \qquad (25)$$

$$\Omega\left(t_i^\vartheta\right) \le \Omega_{max} - g\ \forall\ t_i^\vartheta \in$$

$$\in [\ pt_1, pt_2, \dots pt_\vartheta \dots, pt_{\vartheta_{max}}\ ], \qquad (26)$$

$$\Omega\left(t_{i+1}^\vartheta\right) = \Omega\left(t_i^\vartheta\right) + \left(\sum_{n=1}^{N}\sum_{m_n^s=1}^{M_n^s}\sum_{s=1}^{S} Z_0^{sm_0^s}\left(t_i^\vartheta\right) * h^s\right) -$$

$$-\left(\sum_{n=1}^{N}\sum_{m_n^s=1}^{M_n^s}\sum_{s=1}^{S} \overline{Z_0^{sm_0^s}}\left(t_i^\vartheta\right) * \gamma^s h^s\right) + g\gamma_g^{t_i^\vartheta}, \qquad (27)$$

where γ^s is the factor of occupancy of an urban vehicle, $\gamma^s \in [0; 1]$;

$\gamma_g^{t_i^\vartheta}$ – the factor of occupancy of a suburban electric train arriving or departing at the moment

t^{ϑ}_{i}, $\gamma_g^{t_i^{\vartheta}} \in [-1; 1]$, if at the moment t^{ϑ}_{i}, the train does not depart $\gamma_g^{t_i^{\vartheta}} = 0$.

Thus, the considered problem can be mathematically formulated as finding the minimum $f = \sum_{t=0}^{T} \Omega(t_i^{\vartheta})$ $f \rightarrow min$ subject to respect of all the above constraints.

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Information about the authors:

Vakulenko, Sergey P., *Ph.D. (Eng), Professor, Director of the Institute of Management and Digital Technologies of Russian University of Transport, Moscow, Russia, vakulenkosp@mail.ru.*

Evreenova, Nadezhda Yu., *Ph.D. (Eng), Associate Professor at the Department of Management of Transport Business and Intelligent Systems of the Institute of Management and Digital Technologies of Russian University of Transport, Moscow, Russia, nevreenova@mail.ru.*

Kalinin, Kirill A., Ph.D*. (Eng), Senior Lecturer at the Department of Management of Transport Business and Intelligent Systems of the Institute of Management and Digital Technologies of Russian University of Transport, Moscow, Russia, kalinin.k.a@mail.ru.*

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