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SCHEDULING TECHNIQUE OF ROUTE VEHICLES ON DUPLICATING STRETCHES

Summary. Schedule optimization is a proven strategy to improve service quality for public transport networks. However, current research mostly optimizes schedule design using prior knowledge of users' routings, ignoring the optimization of public transport schedules on duplicating stretches of route vehicles. This article presents a new alignment technique of time intervals between consecutive vehicles of different routes on duplicating stretches, considering existing public transport networks in attaining optimization of public transport schedule. Scheduling technique of route vehicles on duplicating stretches includes some steps: analysis of public transport network and determining a lot of duplicating stretches,

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calculation of the optimal time intervals among arrivals of route vehicles and alignment of these intervals among consecutive route vehicles on duplicating stretches, realization simulation model of urban passenger transport within the simulation modeling system of GPSS World. Furthermore, testing the optimization technique of route vehicle scheduling, analysis of the quality of adjusted schedule with route vehicles of different kinds included, and determining the optimization efficiency for duplicating stretches. The adjusting technique of urban passenger transport schedule allows to increase movement steadiness of consecutive vehicles of different routes on duplicating stretches, adjust traffic intervals for each route, shorten the traffic load on stations, reducing idle time and queue lengths of route vehicles in front of transport stops and also minimize waiting time for route vehicle by those passengers who can be transported along several routes. Improving the bus schedule on duplicating stretches in Gomel is illustrated demonstrating the technique developed. This scheduling technique can be used by carriers and transport operators to improve the quality of services provided.

Keywords: scheduling technique, route vehicles, duplicating stretches

1. INTRODUCTION

Accessibility and quality of urban passenger transport determine the real living standard and social climate, while reducing its attractiveness leads to the use of personal vehicles by passengers, which has a negative impact on the environmental situation of cities [1-7]. Therefore, the task of public transport efficiency improvement and development of activities on improvement of public transport operation through qualitative scheduling is an urgent challenge.

An efficient and rational schedule of urban public transport could provide:

- regularity of the route vehicle traffic;
- high-quality public service for passengers and travel with minimal waste of time;
- traffic of vehicles in accordance with passenger traffic on routes;
- coordination of the route vehicle traffic with the traffic of other types of passenger transport.

Several approaches and computer-aided software packages have been dedicated to the scheduling methodology of passenger transport. According to the different features, the approaches developed can be categorized into three groups: (i) interactive graphical visualization and optimization approach, (ii) mathematical programming and analytical modeling approach, and (iii) heuristic and metaheuristic approaches (genetic algorithm, simulated annealing, and ant colony optimization).

In the first group, interactive graphical optimization techniques were proposed by a few researchers. Cao et al. [8, 9], developed real-time schedule adjustments for autonomous public transport vehicles The solution methodology proposed is based on time-space graphical techniques using multi-criteria decision analysis to minimize schedule changes as the primary objective, as well as to reduce travel time and active energy consumption. Further, Krause et al. [10] proposed a visualization system, BusVis, that provides overviews of a transport system in terms of distance and travel time, and comparisons between different routes.

The second approach widely found in the literature adopts the mathematical programming models. Liu and Ceder [11] developed a bi-objective, bi-level integer programming model, taking into account the interests of public transport users and operators in attaining the optimization of public transport timetable synchronization integrated with vehicle scheduling and considering user demand assignment. Furthermore, Wu et al. [12] proposed a bi-level programming model in which the schedule design and passenger route choice are determined simultaneously via two travel strategies: non-adaptive and adaptive routings. Additionally, Yin et al. [13] offered the use of mixed-integer linear programming approaches for metro train scheduling.

The third group employs heuristic and metaheuristic approaches: genetic algorithm, simulated annealing, and ant colony optimization. Carosi et al. [14] proposed a multicommodity-flow type model for integrated timetabling and vehicle scheduling and a diving-type metaheuristic approach for the problem. While Naumov [15] provided a genetic-based algorithm of the public transport lines synchronization in a transfer node. The described approach is based on the simulations of the demand for changing the public transport lines with a genetic algorithm. Subsequently, Gorokhova [16] and Kochegurova et al. [17] developed an algorithm for generating schedules of passenger transportation using the ant colony optimization algorithm.

A series of follow-up studies related to the optimization of public transport schedules (for example, Yakimov and Trofimenko [18], Muller et al. [19], Leng et al. [20, 21], Ahmed et al. [22], Banerjee et al. [23], Shelton et al. [24], Dike et al. [25]) have been conducted.

When developing a schedule for urban passenger transport to improve the quality of passenger service, it is necessary to consider the joint stretches of traffic on different routes. If there are several routes servicing a particular stretch in a transport network, then it is necessary to coordinate traffic schedules of different routes on the joint (duplicating) stretches of their traffic by adjusting departure time for each of them to avoid the formation of queues at transport stops.

Thus, a duplicating stretch is a compatible stretch of vehicle traffic on different routes. The length of the stretch that can be considered a duplicate depends on the size of the public transport network. Servicing of duplicating stretches causes some problems: transport queues at transport stops, irregular intervals of traffic vehicle, increasing passengers' waiting time leading to discomfort while traveling.

The problem of improving passenger service quality and efficiency of urban public transport is the alignment of the schedules of different routes on duplicating stretches, thereby contributing to a more regular traffic interval and vehicle occupancy.

2. METHODOLOGY

Scheduling technique of route vehicles on duplicating stretches includes the following steps.

2.1. Analysis of public transport network and duplicating stretches

Urban network is analyzed and its characteristics are defined:
- a lot of routes $M = \{M_1, M_2, \ldots, M_{Nm}\}$;
- a lot of transport stops $S = \{S_1, S_2, \ldots, S_{Ns}\}$;
- frequency of movement on different routes $N_M = \{N_{M1}, N_{M2}, \ldots, N_{Mm}\}$;

- route vehicle's arrival / departure frequency of different routes at each transport stop (according to the existing schedule) $ST = \{ST_1, ST_2, \ldots, ST_{Nst}\}$ [26, 27].

For different routes, it is necessary to determine:
- a lot of duplicating stretches $D = \{D_1, D_2, \ldots, D_{Nd}\}$,
- length of duplicating stretches $LD = \{LD_1, LD_2, \ldots, LD_{Nd}\}$,
- frequency of movement of different routes of duplicating stretches $N_D = \{N_{D1}, N_{D2}, \ldots, N_{Dd}\}$,
- route vehicles arrival / departure frequency of different routes at each transport stop of duplicating stretches $SDT = \{SDT_1, SDT_2, \ldots, SDT_{Nst}\}$,
- social value of service area $KD = \{KD_1, KD_2, \ldots, KD_{Nd}\}$: railroad passenger and bus terminals, facilities of the attraction, large-scale enterprises, educational establishments, etc.

A lot of planned schedule optimization periods $T = \{T_1, T_2, \ldots, T_{Nt}\}$ is defined, for example, every hour, rush hours or periods between rush hours.

Each transport stop S_j in the planned period T is characterized by a vector $(S_j, M_j, N_{Mij}, ST_{ij})$. Each duplicating stretch D_j in the planned period T is characterized by a vector $(D_j, KD_j, LD_j, N_{Dij}, SDT_{ij})$. The next steps are performed for each planning period T.

Duplicating stretches $D = \{D_1, D_2, \ldots, D_{Nd}\}$ are ranked in a descending order of the transport stop amount and number of routes. Social value of service area $KD = \{KD_1, KD_2, \ldots, KD_{Nd}\}$ may also be considered. The routes $MD = \{MD_1, MD_2, \ldots, MD_{Nmd}\}$ with the largest duplicating stretches are determined with the following ranking in an ascending order of route vehicles amount.

The basic transport stop SB_r is assigned for determined routes. The social value of a service area should be considered when choosing a basic transport stop, the stretch length in which routes are duplicated, and the route vehicle frequency of different routes along such stretches.

Compulsory arrival/departure frequency of route vehicles are defined pegging to: passenger service of railway and bus terminals; the beginning or the end of the enterprise performance; the beginning or the end of the working shift, lunch break of route vehicle drivers; the beginning or the end of the classes in the educational institutions.

2.2. Alignment of time intervals among consecutive route vehicles on duplicating stretches

The optimal time interval among arrivals of route vehicles of all routes I^*_{MDk} and duplicating stretch routes I^*_{Dr} at the transport stop is calculated:

$$I^*_{MDk} = \frac{T}{N_{Mk}} \tag{1}$$

$$I^*_{Dr} = \frac{T}{\sum\limits_{i=1}^{n} N_{Dri}} \tag{2}$$

Where:
T – planning period
N_{Mk} – number of runs carried out on the route k at the time interval T,

N_{Dri} – number of runs carried out on the duplicating stretch r at the time interval T,
n – number of routes on the duplicating stretch r.

Boolean assignment matrix is formed [28]. It shows the assignment of route j to time interval i for the basic transport stop SB_r of the duplicating stretch D_r (Table 1):
$x_{ij} = 1$, if route j is assigned to time interval I,
$x_{ij} = 0$, if not,
$x_{ij} = 1^*$ – compulsory assignment.

Tab. 1

Assignment matrix for the duplicating stretch D_r for basic transport stops

Arrival time	MD_1	..	MD_k	K_D	$\|I_D^* - I_i\|$	T_W	$\|I_{MD1}^* - I_i\|$	..	$\|I_{MDk}^* - I_i\|$
t_1	x_{11}	..	x_{1k}	K_{D1}	$\|I_D^* - I_1\|$	T_{W1}	$\|I_{MD1}^* - I_1\|$	..	$\|I_{MDk}^* - I_1\|$
t_2	x_{21}	..	x_{2k}	K_{D2}	$\|I_D^* - I_2\|$	T_{W2}	$\|I_{MD1}^* - I_2\|$	..	$\|I_{MDk}^* - I_2\|$
...	...	..	...	...	...	...	...	..	...
t_i	x_{i1}	..	x_{ik}	K_{Di}	$\|I_D^* - I_i\|$	T_{Wi}	$\|I_{MD1}^* - I_i\|$	..	$\|I_{MDk}^* - I_i\|$
...	...	..	...	...	...	...	...	..	...
t_n	x_{n1}	..	x_{nk}	K_{Dn}	$\|I_D^* - I_n\|$	T_{Wn}	$\|I_{MD1}^* - I_n\|$	..	$\|I_{MDk}^* - I_n\|$
Sum	$\sum_{i=1}^{n} x_{i1}$	..	$\sum_{i=1}^{n} x_{ik}$	$\sum_{i=1}^{n} K_{Di}$	$\sum_{i=1}^{n}\|I_D^* - I_i\|$	$\sum_{i=1}^{n} T_{Wi}$	$\sum_{i=1}^{n}\|I_{MD1}^* - I_i\|$	..	$\sum_{i=1}^{n}\|I_{MDk}^* - I_i\|$

For each time interval of assignment matrix, the next values are defined:

- $K_{Di} = \sum_{j=1}^{k} x_{ij}$: load factor, equal to the number of vehicles arriving at the transport stop on the duplicating stretch;
- $\|I_D^* - I_i\|$: deviation value of intervals among consecutive route vehicles from the optimal value of the duplicating stretch,
- $\|I_{MDk}^* - I_i\|$: deviation value of intervals among consecutive route vehicles from the optimal value of the route k,
- $T_{Wi} = I_i \lambda_i$: passengers' waiting time, where λ_i is the intensity of incoming passenger traffic using vehicles of the duplicating stretch.

Using the assignment matrix, route vehicle schedules are aligned with the following:
- intervals between vehicles on the duplicating stretch ($I_{D1} \approx \ldots \approx I_{Di} \approx \ldots \approx I_{DN}$) and between vehicles of the routes on this duplicating stretch ($I_{MD1} \approx \ldots \approx I_{MDi} \approx \ldots \approx I_{MDN}$) become equal,
- load factor K_{Di} for arrival time t_i is equal 1, this means that only one vehicle from the duplicating stretch is located at the transport stop,
- decreases the value of passengers' waiting time T_{Wi}.

It is necessary to minimize the value of the objective function – the amount of intervals deviation $D_r(I)$ between consecutive route vehicles from optimal value for the time interval T:

$$D_r(I) = \sum_{i=1}^{N_D} |I_{Dr}^* - I_i| + \sum_{i=1}^{N_{M1}} |I_{MD1}^* - I_i| + \sum_{i=1}^{N_{Mk}} |I_{MDk}^* - I_i| \rightarrow \min \qquad (3)$$

After the comparison assignment matrix and $D_r(I)$ before and after the optimization, the decision on formation of the schedule of duplicating routes is adopted.
Then calculation of traveling time through the rest transport stops of the route regarding the basic stop and transition to the next duplicating stretch is performed.

2.3. Simulation modeling of route vehicles on duplicating stretches

The next step is to realize the simulation model of duplicating stretches within the simulation modeling system of GPSS World [29, 30]. This makes it possible to test the scheduling technique of route vehicles on duplicating stretches.

A mathematical model of the movement of traffic flows going through a duplicating stretch can be represented as a queuing system. Its graphical representation is shown in Figure 1.

The proposed queuing model of duplicating stretches is developed in the GPSS World simulation automation package.

The properties of the simulation model of duplicating stretches have been tested and studied. The simulation model test includes two stages: verification and validity check. At the verification stage, the correctness of the operating algorithm of duplicating stretches simulation model using the model's interactive single-step debugging properties was checked.

Because of the simulation experiment on the developed simulation model, transport stop load factors at route vehicle traffic on duplicating stretches and lengths of queues on the transport stops were obtained.

2.4. Analysis of the quality of adjusted schedule with route vehicles of different kinds included

For each basic stop, is formed a general assignment matrix, involving all duplicating stretches with routes MD_1, MD_2, etc. passing through chosen transport stops and other route vehicles M_1, M_2, etc. In addition, it includes information on route vehicles of all kinds (K_{DM}) arriving at each transport stop.

For each type of route vehicle, the transport stop load factors are calculated, and subsequently, summarized to formulate the common load factor (K_{DO}). Based on the values of the transport stop load factors, the lengths of queues on the transport stops are defined.

Comparison of statistical data (common transport stop load factor and average queue length on the transport stop), obtained through the simulation modeling in GPSS World, with results obtained during the implementation of the methodology proposed, is being conducted.

Then synchronization of the adjusted route vehicle schedules considering schedules at stops being used as transfer facilities for passengers is executed. When it is impossible to synchronize the obtained route vehicle schedules among each other, some steps must be repeated.
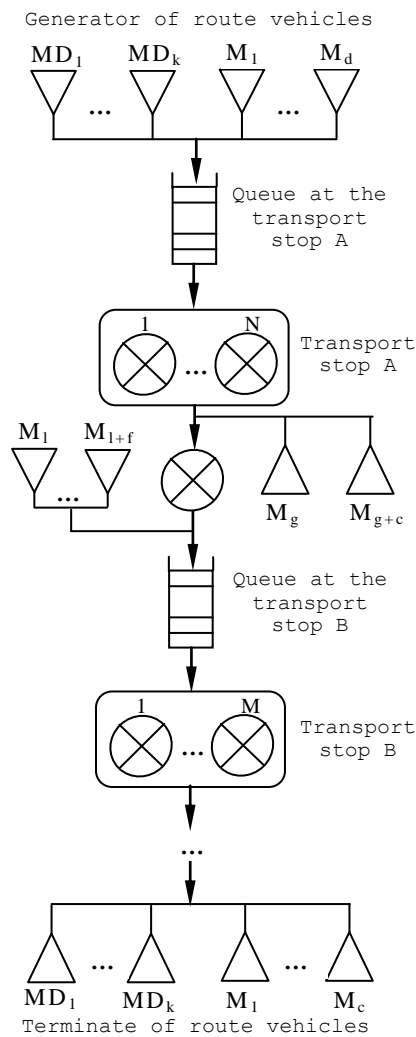
Fig. 1. Mathematical model of a duplicating stretch

2.5. Determining the optimization efficiency for duplicating stretches

The efficiency of optimizing public transport schedules on duplicating stretches is calculated:

$$F_r^* = D_r^0(I) - D_r^*(I) \tag{4}$$

Where:

$D_r^0(I)$ – deviation between consecutive route vehicles from optimal value before optimization,

$D_r^*(I)$ – deviation between consecutive route vehicles from optimal value after optimization.

3. APPLICATION

Scheduling technique of route vehicles on duplicating stretches was tested in the public transport network of Gomel. The city of Gomel with about 530,000 inhabitants is the administrative center and the second-most populous city in Belarus. Currently, transportation of passengers in Gomel is carried out on 81 regular bus routes. There were defined six duplicating stretches provided for buses movement of three or more routes (Table 2).

Tab. 2

Parameters of duplicating stretches

Duplicating stretch	Bus routes	Transport stop amount	Sum of stops and routes	Length of duplicating stretch (km)
D_1: "Institute "Gomel project" – Ogorenko street"	No 17, 18, 34	13	3 + 13 = 16	7,5
D_2: "Railway station – First school"	No 35, 55, 58	12	3 + 12 = 15	8,47
D_3: "Railway station – "Gorelektrotransport" "	No 10, 19, 43	10	3 + 10 = 13	4,94
D_4: "Railway station – Cinema "October" "	No 20, 21, 40, 52	8	4 + 8 = 12	4,47
D_5: " "Medgorodok" – Technical University named after P.O. Sukhoi"	No 16, 17, 26, 33	8	4 + 8 = 12	3,39
D_6: "Railway station – Palace of culture "Gomselmash" "	No 6, 8, 8A, 9	7	4 + 7 = 11	3,93

Duplicating stretches were ranked in a descending order of the sum of stops and routes on the stretch, and also optimized the main bus route schedules. Performance evaluation of the adjusted schedule by six duplicating stretches is presented in Tables 3-4.

Tab. 3

Optimization result of the schedule by six duplicating stretches
for the period between rush hours

D_i	Before optimization			After optimization			$F_r^*(I)$
	$\lvert I_D^* - I_i \rvert$	$\lvert I_{MD}^* - I_i \rvert$	$D_r^0(I)$	$\lvert I_D^* - I_i \rvert$	$\lvert I_{MD}^* - I_i \rvert$	$D_r^*(I)$	
D_1	33	35	68	15	32	47	21
D_2	24	34	58	6	18	24	34
D_3	35	23	58	3	20	23	35
D_4	26	32	58	9	17	26	32
D_5	28	34	62	9	25	34	28
D_6	20	31	51	5	28	33	18
Sum	166	189	355	47	140	187	168

Tab. 4

Optimization result of the schedule by six duplicating stretches for rush hours

D_i	Before optimization			After optimization			$F_r^*(I)$
	$|I_D^* - I_i|$	$|I_{MD}^* - I_i|$	$D_r^0(I)$	$|I_D^* - I_i|$	$|I_{MD}^* - I_i|$	$D_r^*(I)$	
D_1	32	20	52	11	17	28	24
D_2	24	34	58	9	28	37	21
D_3	34	38	72	9	33	42	30
D_4	39	32	71	4	29	33	38
D_5	31	44	75	13	45	58	17
D_6	15	27	42	2	23	25	17
Sum	175	195	370	48	175	223	147

The value of the efficiency of optimizing public transport schedules for the six duplicating stretches is equal to 168 minutes – for the period between rush hours and 147 minutes – for rush hours.

Due to the traffic schedule optimization on the six duplicating stretches,
- the traffic intervals of buses for each route separately were aligned, deviation value of intervals among consecutive buses from the optimal value reduced by 26% for the period between rush hours, and 10% for rush hours;
- in total deviation value of intervals among consecutive buses from the optimal value by the six duplicating stretches reduced by 47% for the period between rush hours, and 40% for rush hours;
- waiting time for route vehicles by passengers that can be transported along several route options was reduced by 27% for the period between rush hours, and 28% for rush hours.

The obtained optimization results may be used by the Open Joint Stock Company, Gomeloblavtotrans, for improving the quality of public passenger transportation.

4. CONCLUSIONS

Using the scheduling technique of route vehicles on duplicating stretches allows to:
- determine the optimal vehicle traffic intervals for each route, considering duplicating stretches,
- coordinate the movement of route vehicles on duplicating stretches,
- determine the optimal number of vehicles on routes,
- reduce waiting time for route vehicles for passengers that can be transported using several route options,
- increase uniformity of vehicle occupancy,
- reduce the load on transport stops.

While optimizing the existent schedule, particular consideration was given to reducing transport delays due to lack of forced idle time of route vehicles in front of a transport stop (waiting for an opportunity to drive to it), and subsequent accelerations, there is also the effect

of reducing economic (additional fuel consumption) and environmental (from emissions of air pollutants) losses.

Improving the bus schedule on duplicating stretches in Gomel was conducted to illustrate the effectiveness of the proposed technique.

Experimental researches have shown the applicability of the developed technique in practice.

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