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# REVIEW ON OPTIMIZATION MODELS AND METHODS FOR SHUTTLE URBAN AND MAIN TRANSPORT TIMETABLES AND TRAFFIC SCHEDULES

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Review for used at the moment models and methods for the creation and optimization of shuttle timetables for urban and main transport is given in the article, major differences between post-Soviet and foreign experience in the technology of timetable and traffic schedule creation are considered. The article contains phased analysis of approaches to planning the work of urban transport. The issues of dividing the city transport network into routes, the problems of vehicle distribution between them are given, the mathematical models of shuttle transport timetables, the assignments of real vehicles of certain types to squads and drivers distribution between them for each date are presented, major reasons for using aperiodic urban transport traffic schedules on post-Soviet area are pointed. The history of the development of software automation systems for urban transport traffic schedules is narrated, there're considered major approaches, implementing an automation for the creation of periodic, aperiodic and hybrid timetables and traffic schedules, for to develop modern informational systems for the being considered purposes.

**Keywords:** shuttle transport schedule; periodic traffic schedule model; aperiodic traffic schedule model; hybrid traffic schedule model; urban transport.

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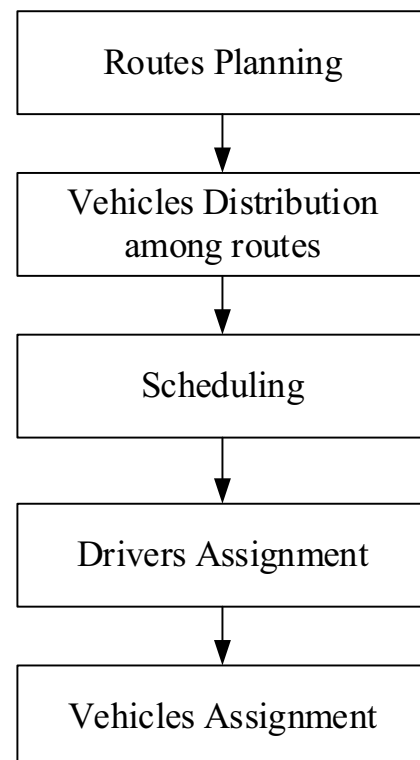
## ▼ Introduction

Permanently growing traffic flows require a constant improvement of the planning quality for the organization of urban and mainline transport work. Various mathematical models and methods were invented for transport planning for different types of transport: railway [1–3], air traffic [4, 5], models for urban underground [6] or ground [7–10] transport and so on. Most of technologies and planning tools for them contain following stages, which are in Fig. 1.

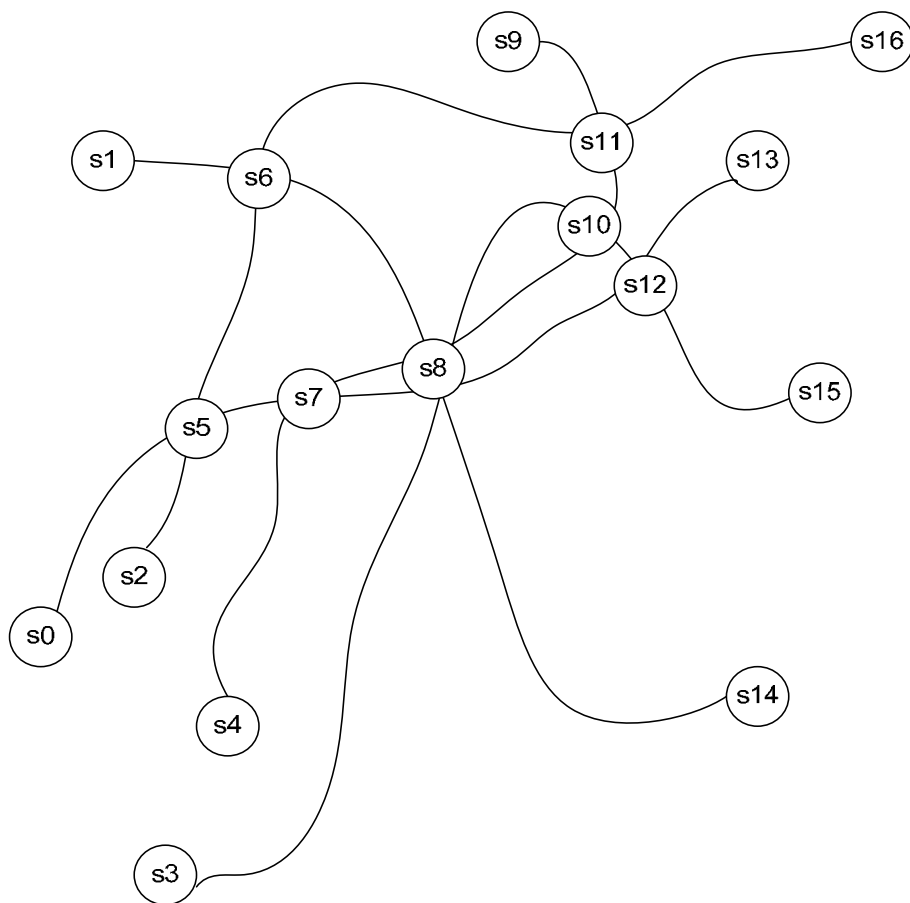
The main goal of this article is collecting approaches and analyzing methods of transport planning. According to the goal of the article, main issues are research of main methods of planning routes, creating timetables, drivers and cars assignment. To achieve all issues let us analyze all stages of planning process.

### 1. Public Transport Network Presentation

The first stage of the planning movement process is creating of routes and lines. It consists of planning public transport routes and traces for them including all control points. Public Transport Network (PTN)



**Fig. 1.** Stages of route transport planning



**Fig. 2.** Example of Public Transport Network

can be represented as a multigraph which paths are made up of route traces and vertices are control points  $cp_i \in \{CP\}$ .

PTN is usually displayed as a layer on a city map. PTN can be presented in a graphic view or as a sparse matrix which is shown in details in [7, 11].

Each path connects neighbouring control points. Control points are depots, end stations, stops and intermediate points, which are usually intersections where vehicle can change movement direction.

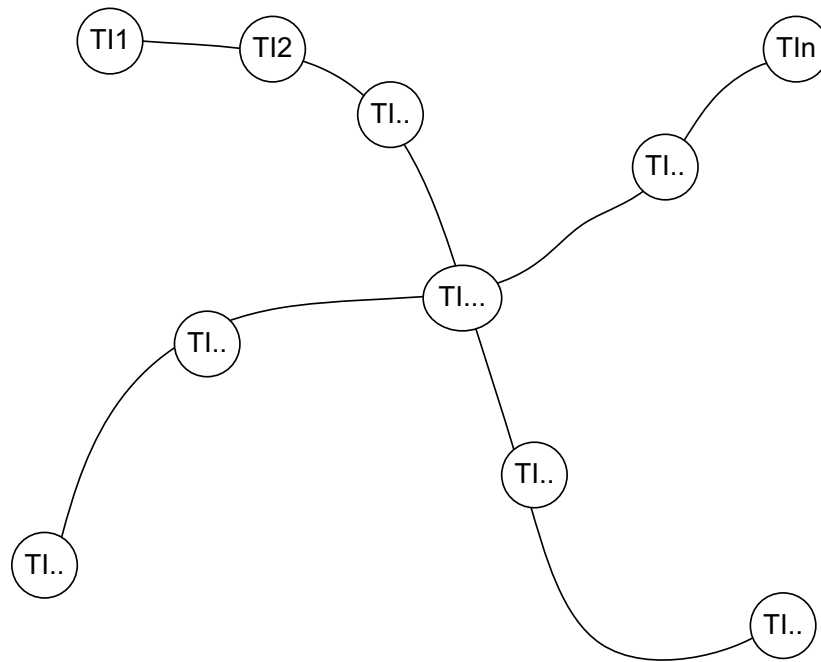
The second stage is distribution of vehicles (or rolling stock for railway transport system) between routes. This process is also called frequency planning which means calculating number of cars for every route in a certain period. Work frequencies are substantial for passengers as they affect waiting times on complex routes when passengers change routes and wait for a vehicle on the new route. It is especially considerable for minimizing total passengers' transfer time as a criterion schedules optimisation [7].

## 2. Event Activity Network and stages of transport work planning

Scheduling (or timetabling) is the most important and complicated part of planning the route transport operation at all levels of traffic work.

Vehicle schedule itself is the most considerable document for every commercial transport company as it contains the quantity and parameters of transport work to be paid from a budget or common passengers. It is also the main document for passengers who plan transportation inside a city. Sometimes schedules are optimized only for special districts of a city [6, 8] or even for special groups of passengers: for example, for people with limited mobility [12].

At this stage, presentation of data is usually changed from PTN multigraph to an Event Activity Network (EAN). Events in this case are arrival times and departure times of route vehicles. EAN is a graph of times, where each vertex is independent time value and each edge means a logical nexus between time values (in Fig. 3).



**Fig. 3.** Example of Event Activity Network

Scheduling process consists of two stages: generation of schedule structure (races, dinners, driver changes, stop durations for technical overview and so on) and solving the main issue of the schedule's theory: to find a feasible schedule. A schedule is feasible in case it corresponds current capacity restrictions, durations of movement between control points, changing and other limits of stop times [7]. So the main problem of schedule's theory is calculating arrival and departure times for the schedule of concrete structure. For solving the first issue — generating schedule structure — usually different heuristic approaches are used depending on local legislation and technology peculiarities. The last issue (solving main problem of the schedule's theory) is the most popular in articles because there are only several mathematical models.

Depending on the mathematical apparatus used to create schedules route vehicle transport, they are divided into two types: periodic and aperiodic [10]. These models are described in various sources [7, 10, 11, 13] and they will be considered more in details later in this article. Special tools, such as software emulators, are used to check feasibility of schedules [1].

Distributing drivers and cars among warrants are last steps of operational planning. These steps are very important for drivers, conductors and for a

transport company in the whole, but not so significant for passengers: data with assignment of drivers, conductors and cars to specific cars are usually part only of internal business processes of the transport company and it is not published outside of the enterprise.

Drivers' assignment is the process of allocating real drivers and conductors between warrants of the schedule for all routes of the current day. It contains two stages: dividing of warrants into several driver change parts (in general) and assigning of real drivers and conductors to driver change parts. A driver or conductor change part is part of the change when one driver (or conductor) works on this vehicle.

Splitting of warrants for driver change parts in Russia and other former USSR countries is usually done during the scheduling process due to the stable labor law, which provides the same conditions for all cities and transport enterprises. In Western European countries situation splitting warrants into driver change parts differs due to many local regulations of the current company from the labor law and driver unions in enterprises [10]. It is hard and expensive to formalize this technology because it is unique for every company. Operational process of a transport company and labor laws make a great impact on it in general case for work of transport enterprise [14].

The second stage of the drivers' assignment is setting of real drivers and conductors to change parts. The main purpose of this stage is allocation of change parts between drivers and conductors to follow the law and to make the total work time during the whole month working hours nearer to normative value.

The last step of planning is cars assignment. It is the process of real vehicles assigning to warrants. Number of free vehicles for each depo depends on maintenance schedule for the current day.

The most complicated problem from all these issues is scheduling problem. While events in non-periodic schedules are arranged in a linear chronological order, events in periodic schedules have a cyclic chronological order with period *Period*.

### 3. Aperiodic schedules

Initially, there were two different schedules flavors from the point of mandatory repetitions of events. The first type of schedules, which is still quite popular now, are aperiodic schedules, also called non-cyclic or non-periodic. Another flavor are periodic schedules.

Aperiodic schedules were the first ones for trains and ships, and were associated with a small level of vehicles moving [10].

Aperiodic (also non-cyclic — see publications [7, 10, 11, 13]) schedules are schedules with no necessary repeat of events after a specified time period *T*.

So there is no one repetitive interval.

Arrival and departure times are calculated as stand-alone values.

Events, relatively to public urban transport, are times of arrivals ( $T_{Arr}$ ) and departures for end stations ( $T_{Dep}$ ), or more broadly, arrival and departure times for all control points which every coach passes.

There are different limitations, which effect on intervals aligning:

- departures of previous vehicles;
- departures of following vehicles (if they are already generated in the schedule);
- min and max limitations on stop times for the current control point;
- driver medical examination points working hours;
- dinner hours for vehicle teams (drivers and conductors);

- recommendations for technical stops of coaches;
- restrictions of day working hours for vehicle teams.
- working hours of canteens for coach teams on end stations;
- depo and end stations working hours;
- other events, which occur during vehicles movement.

These limitations restrict departure intervals by two limits [*Start*, *End*].

The uniformity of departure intervals usually is the objective optimization function of intervals aligning.

Feasible Distribution algorithm based on linear programming for flow approach was the first solution of this problem and it was described in [15].

The problem is solved using a modified algorithm, initially proposed for solving the coloring issue. One more method for solving of this problem was suggested in [7].

To calculate vector of independent departure times [*TI*] standard grid with equal intervals is created. Standard grid is a vector with the same size *k* as [*TI*], in which time values are distributed inside [ $TI_0$ ;  $TI_k$ ] the most smooth way. So every time in [*Tin*] can be calculated according to the formula:

$$TIn_i = Round\left(TI_0 + TI_k - \frac{TI_0}{k \cdot i}\right), \quad (1)$$

where Round — is a round function according to common math rules to the nearest integer (in case of using only discrete time values in the timetable).

[*Tin*] is the best schedule without considering {*U*} и {*V*} vectors.

Optimized times [*TI*] can be obtained using linear combination of [*TI*] and [*Tin*]. Suppose *s* is a coefficient in the linear combination:

$$s = Min\left\{s, \left\{ \begin{array}{l} \frac{V_i - TIn_i}{TI_i - TIn_i}, TI > TIn_i \\ \frac{U_i - TIn_i}{TI_i - TIn_i}, TI < TIn_i \end{array} \right. \right\}. \quad (2)$$

After getting *s* times of TI can be recalculated as a linear combination of an old vector [*TI*] and ideal vector [*Tin*]:

$$[TI] = s[TT] + (1-s)[TIn] \quad (3)$$

Applying liner programming for intervals aligning is a typical approach solving the main schedule problem for aperiodic schedules. This feature provides the polynomial complexity, which was shown in [15]. The complexity of the algorithm is polynomial. . Imposition additional conditions can reduce the problem to the number of NP-hard ones. Such examples are, in particular, the problem of creating schedules taking into account passenger routes [11] and, sometimes, capacity restrictions of the infrastructure [13].

Polynomial complexity is one of the most important benefits of aperiodic schedules, especially for slow processors of personal computers. Aperiodic schedules were popular in Poland, Hungary, USSR and, initially, all over the world, during XX century for urban transport. However, adjustment of intervals and stops durations during a day, different events during a change (such as technical stops) make matching of different routes difficult and unobvious for passengers.

Later after supply of new vehicles, when frequencies became higher, transport companies decided to use shorter intervals and to avoid binding of drivers to cars during the whole shift. So the technology became closer to periodic timetables. Although the problem of movement in one level with cars remained. Due to this fact various run times for different day times remained.

#### 4. Periodic schedules

Periodic (cyclic) schedules are those whose actions are repeated after a specific (usually small) period of time *Period* and those whose contains limitations  $[U, V]$  with lower and upper bounds. They are preferable for passengers, provided that *Period* is a relatively small value [10]. A mathematical model for periodic schedules was proposed as Periodic Event Schedule Problem (PESP) [16]. In the same paper, a proof is given that the problem of finding an admissible periodic schedule is proved as NP-hard. Different NP-hard algorithms can be used to generate the best schedule from all feasible [10, 17]. For this reason, various approaches and different complicated search methods were used to solve the task, which, in the worst case, have exponential complexity [18].

Searching of a suitable schedule is the main issue of the scheduling theory.

It is a problem of calculating appropriate arrival and departure times of cars with limitations for known structure of the schedule. In some works it is called departure intervals aligning.

Other problems, such as generating structure of races for each driver shift, calculating of parking lots for maintenance, organizing driver changes in stops and end stations, calculating number of shifts regarding to all restrictions and so on are not included in the main task of the scheduling problem. The issues of periodic schedule developing and optimization are presented in [2, 3, 19].

Periodic schedules are better for passengers because of fixed intervals *T* between departures for vehicles. Morning and evening rush hours ruin these approach in case of movement in the same road traffic with cars.

Despite positive traits, many countries around the world switched to periodic train schedules for main and city route transport in the 20th century. Potent computers gave a possibility to use practically NP-algorithms including periodic schedules, first of all, in small countries because of easier PTN multigraph. So periodic schedules were deployed in Denmark (1974), Switzerland (1984), Belgium and Austria (1991). The migration from noc-cyclic to periodic schedules of mainline train movement began in 1979 from intercity trains of the country and was completed in 1993 [10]. Cyclic schedules are widely used all over the world and allow to optimize waiting times. A future area of development is the planning of traffic schedules, including the need for docking various trains at transfer points and hubs.

Some special traits of transport work in Russia made using such schedules inexpedient or even impossible.

Some researchers distinguish a third type of transport schedules, calling them hybrid [9, 19]. These schedules have small usually constant intervals between departures during one period. There will be another stable interval for another period of the day. This planning technology can be used in transport companies where one driver is able to change car during one shift. So hybrid schedules are actual for routes with new vehicles of one type.

## 5. A General Overview of Main Technological Features in Russia and Former Countries of the Warsaw Pact

The main schedule technology features of the Warsaw Pact countries and the USSR were the following. (accordingly, travel times change significantly over periods of the day due to traffic congestion), the possibility of assigning teams (driver and conductor) to vehicles, rigid schedule binding to the work schedules of drivers, providing lunches to crews while vehicles are parked at terminal stations, etc. [7, 9, 10].

### 1. Movement of fixed-route vehicles mainly in the general flow (a few number of dedicated lines)

This led to unfixed run times for different day periods especially for rush hours because of traffic jams. Day time is usually divided by rush hours to several periods: time before morning peak hours (for example, from start of a day till 7 a.m. or 9 a.m. for days off), morning peak hours (from 7 a.m. (9 a.m.) till 9 a.m. (11 a.m.)), time before morning and evening peak hours (from 9 a.m till 4 p.m.), evening peak hours (from 4 p.m. till 8 p.m.), time after evening peak hours (from 8 p.m till end of a day). The exact values of periods are given only as an example; practically they differ from one city to another or even from one route to another.

### 2. Binding of drivers to cars during the whole shift

The second peculiarity is binding of drivers and conductors to certain coaches during the whole shift. It means that cars stand idle during driver and conductor lunches and special technological stops.

### 3. Logical binding of transport brigades to cars

The next peculiarity is permanent binding of transport teams (i.e. drivers and conductors) to cars during long period. A large number of old cars in post-soviet countries which are used in one transport company and each of them has their own traits and problems tends to this fact. This feature is usually called logical binding of transport teams to routes and cars. Every brigade consists of a driver and a conductor.

### 4. Criteria of optimization

The fourth peculiarity is a criterion of optimization, which is used to create schedules. The most popular one is minimizing total passengers' travel time. The only problem is getting correspondence matrixes according to route traces to calculate total travel time. So in most of cases there is no any

special equipment on cars to calculate passengers. The main issue with this approach is impossibility quickly to get changes in correspondence matrixes and run times for traces.

### 5. Problems with schedule synchronization between urban and railway transport, which was analyzed in [20]

The main practically used criterion of schedule optimization in such cases is intervals' equality. Departure intervals are commonly used simply because they are the more important for passengers. The main idea of this criterion choosing is that in general uniform distribution of departures (during one period of day) is more preferable for passengers than the other criterions.

Using aperiodic schedules provides an opportunity to reduce bad periodic schedules' effects that were mentioned above. Unfixed intervals and stops allow to avoid big intervals during lunches. Meanwhile it is less convenient for passengers, especially in case of composite trips.

## 6. Computer-Aided Design System for Creating Schedules

These differences are relevant now, so we will consider them in more detail.

As a result of a discrete change in the values of travel times by hours of the day, when constructing a schedule, a countdown problem arises when, when calculating, for example, arrival times at the end stations or other control points  $T_{Arr}$ , departure times of going out of the depo, departure times from end stations or other control points  $T_{Dep}$ , times of returning to depo. It is possible that the exact result of calculating previous value of time from current value simply does not exist if the time is near the border of periods of the day.

Because of connection of traffic schedules to the work schedules of transport teams, there is a problem of downtime, for example, for such urban transport, such as tramways, trolleybuses and buses, during technical stops or lunches.

In addition, if such technological restrictions exist and periodic schedules are used, the minimum fixed duration of the period will be equal to the maximum technological stop time (technical stop, dinner, driver change duration), which, as a rule, is unacceptable for city transport because of a long time of a transport idle.



Data formalization of scheduling source in case of Russian conditions was published in [7, 10].

For schedules with the above restrictions, the development of periodic schedules with a period  $Per$  are used in practice only if the fixed interval is quite small. For example, technical and lunch stops durations are comparable with the duration of a standard stop. In real end stations and depots, quantity of vehicles which are able to stay at the same moment on this parking lot differs significantly from one place to another. Practical setting long stop durations to follow all restrictions including long dinner stops and fixed intervals will provide significant downtime of the rolling stock. It is unacceptable for most transport companies. This fact explains popularity of aperiodic schedules in city transport in Russia and other former Soviet countries.

The first efforts to automate the process of the schedule designing for city transport (foremost, for buses) were made in the USSR in the 60s years of the XX century in Moscow [21]. However, the results of this work were not widely used in practice because of slow computers at those times [22]. The solve of the task was limited by only two end stations without shunting work and trips, the movement between which was carried out along one main trace. A complete list of restrictions was published in [22]. The main achievements of this solution [22] were the matrix representation of schedules as a modified table without overtaking of vehicles and the practical implementation of invented methods as computer programs, etc.

Some results of the modern software development for automating city transport operational technology in Russia are given in [9, 23].

So in [23] the Automated Control System for Urban Electric Transport, is used in St. Petersburg, was described. It has a module client-server structure. In source [10] the system which used in Moscow and many other Russian cities was presented. By the way, all software, described in [10] are only some reviews, but they do not carry a definition of mathematical models which are used in this software.

This explains the need to develop a separate model of aperiodic urban transport schedules, taking into account the above features of the organization of traffic that are characteristic of our country.

## Conclusion

So main mathematics transport schedule models are successfully analyzed and main tasks, which were declared in the start of the article, were considered in the article.

As a further proposal of research, schedules synchronization of different types (periodic, aperiodic and hybrid) for distinguished routes in the same EAN is interesting with classifying route crossings and end stations for PTN. CAD systems, which gives the possibility to design schedules using different types of periodic, aperiodic, and hybrid models for the same PTN, can be developed as a practical usage of these theoretical models of EAN.

It is also interesting to analyze times of transition to a new interval for hybrid schedules especially in case of routes synchronization.

There is one more important problem for aperiodic schedules: synchronization of passing through intersections for vehicles from opposite directions during one traffic light cycle. ▲

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## Обзор моделей и методов оптимизации расписаний и графиков движения маршрутного городского и магистрального транспорта

### Информация об авторе

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**Аннотация:** В статье опубликован обзор используемых в настоящее время моделей и методов построения и оптимизации маршрутных расписаний городского и магистрального транспорта, рассмотрены основные отличия технологии построения расписаний и графиков движения в России от зарубежного опыта. В статье осуществлен поэтапный анализ подходов к планированию работы городского транспорта. Рассмотрены вопросы разбиения транспортной сети города на маршруты, проблемы распределения транспортных средств между ними, приведены математические модели расписаний движения маршрутного транспорта, назначения реальных транспортных средств определенных типов на наряды и распределения водителей между ними на каждую дату, указаны основные причины использования аperiodических расписаний городского транспорта на постсоветском пространстве. Изложена история развития программных комплексов автоматизации построения расписаний движения городского транспорта, рассмотрены основные подходы к разработке современных информационных систем такого назначения, реализующих автоматизацию построения периодических, аperiodических и гибридных расписаний и графиков движения.

**Ключевые слова:** расписание маршрутного транспорта; модель периодического расписания; модель аperiodического расписания; гибридная модель; городской транспорт.

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