Public transport synchronization problem and the possibility of its compliance with social distances on the example of regional airport hubs

V A Borodavkin and Yu A Kapitonov
Baltic State Technical University “VOENMEH” named after D. F. Ustinov, 1, ul. Krasnoarmeyskaya 1-ya, Saint Petersburg, 190005, Russia
E-mail: pror-ur@bstu.spb.su, madlenru@mail.ru

Abstract. The problem of organizing passenger transfers at regional airport hubs in terms of the pandemics is considered in the article. On the one hand, public transport has become a dangerous place for the spread of diseases. On the other hand, it is necessary for the existence of key sectors of the economy. A mathematical model of the synchronization of the arrival and departure of aircraft is proposed as the assignment problem. Unlike other available models, the goal is to slow down the speed of passenger flows with the ability to maintain social distance in the area of the transfer airport. The proposed model has a fan pattern schedule scheme, in which, until a certain estimated time, only arrival of vehicles is carried out and after this estimated time only departure. Aviation regional interchange hubs located in the Siberian part of the Russian Federation were considered in numerical experiments. To detail the restrictions, the service regulations for transit flights on domestic airlines were used. Thus, it is proposed to implement one of the concepts of transport operation in a pandemic, especially to abandon the speed as a service in favor of passengers' safety.

1. Introduction
Air transport in the Russian Federation has long been an important component of the modern economy. Considering the significant geographical space of Russia, it is often a key transport industry providing high-speed transportation of passengers, urgent and important cargo. At the regional level, the interaction of both different types of transport and the organization of interaction between long-range and regional air transport are also essential. The current situation with the coronavirus pandemic requires a revision of the implementation of transport concepts. On the one hand, public transport has become a dangerous place for the spread of the epidemic. On the other hand, it is necessary for the existence of key sectors of the economy that ensure the livelihoods of Russian citizens.

In the middle of 2020, publications are mainly based on the study of the experience of transport operation during the first wave of the pandemic and a number of observations in various countries, it is noted [1 and others]:

- the conditions of transfer do not meet the social distance requirements. In land transport, there is a rule of 3–5 people per 1 m² for standing passengers. In air transport, there is a goal to reduce the distance between the rows of seats, especially among budget airlines;
public transport should operate in conditions of a limited amount of services;

- employees of transport companies must ensure the uninterrupted operation of ventilation systems of the internal space of vehicles and antiseptic treatment of internal surfaces.

One of the practical tasks is to ensure synchronization for transfer passengers. Delivery of passengers to the airport, waiting for baggage claim at the relative points, waiting for check-in for the next flight, waiting for an organized boarding gate, and the boarding itself must also include the compliance of social distances.

The article proposes a modification of the method for calculating the synchronization of arrival—departure of aircraft at a regional airport hub that ensures a limited stay at the airport and allows reduction of the speed of passenger traffic at the airport, creating conditions for self-organization of social distances of passengers.

2. Mathematical formulation of synchronization problem

Many authors have made researches on the creation of mathematical models for the optimization and synchronization of vehicle schedules. They can be divided into groups. In countries with high-speed trains as the dominant regional transport (Central European countries), mathematical models use the specifics of railway transport, especially some possibility of regulating the speed of trains. In such mathematical models, the lower and upper boundaries of the onset of temporary events are set. An event is understood as the arrival or departure of a train at a junction. The main optimization criterion is the minimum weighted total transfer time at transport hubs. An alternative criterion is considered to be the minimization of the travel time from one point to another with the presence of a transfer or the weighted sum of the travel time from a set of initial points in the network to another set of points. Problems of this type are proved to be NP-hard. These problems are considered in the works of Schrijver, Nachtigal, Kroon, Liebchen, Peeters, Goerigk, Schöbel and other authors [2–7]. In countries with buses as the dominant regional transport (Mexico, Israel, New Zealand, Australia and others), the authors of the works create mathematical models that are mainly based on linear integer programming. These models use proven, precisely defined reference routes. By setting one time point on the route (for example, the time of arrival at a transport hub), you can immediately determine the time of departure from the starting point of the route. Some authors reduce the problem of planning the movement of passenger transport in the network to a quadratic assignment problem. The mathematical model of synchronization by the Israeli specialist Ceder is the most widespread in the networks of bus passenger traffic [8, 9].

Airlines use the Hub-and-Spoke method, in which passengers and goods are first delivered from the point of departure to the hub, and from there they fly to the actual destination. The use of the Hub-and-Spoke method leads to high utilization of interchange hubs and aircraft during peak hours.

Hubs also help ensure that large aircraft are economically operated on long-range flights. The larger the aircraft and the longer the flight path, the lower the proportional operating cost of carrying a passenger. At the same time, smaller regional airports are also connected to the global air traffic network [10]. A simplified mathematical model is also allows to numerically analyze the economic effect of using hubs in comparison with the scheme of only direct flights. The mathematical model is reduced to the problem of linear programming or linear integer programming, if detailing of the applied infrastructure is needed.

One of the technical possibilities for organizing synchronization is the use of airbridges at airports, which make it possible to reduce the time for passenger transfer between main and regional lines. The work [11] considers the problem of assigning airbridges to flights of arriving aircraft under various technical constraints in order to minimize the waiting time of transit passengers for one of the largest airports in Europe. The article [12], in addition to airbridges, takes into account the operation of domestic airport buses that bring passengers from remote aircraft parking areas.
A common disadvantage of the existing synchronization models is their difficult solvability.

In [13, 14], a model of synchronization of a regional bus transport hub is presented, which is reduced to the assignment problem with additional constraints. In [15], the same model is considered in the application of the railway-bus transport hub. The model uses a fan pattern schedule scheme, in which, until a certain estimated time, only arrival of vehicles is carried out and after this estimated time only departure. If the number of lines under consideration is not more than 10, the problem is solved in the Microsoft Excel.

The considered mathematical models, while minimizing the total transfer time, ultimately lead to the fact that the most loaded vehicles arrive closer to the estimated time and are sent first. Thus, near the estimated time, there is a peak in the movements of passengers in the transport hub. In order to comply with social distances, it is proposed to reduce the speed of passenger traffic at the airport.

The problem of synchronization with the possibility of observing social distances is formulated as follows. You want to find

$$
\min \frac{1}{D} \sum_{k=1}^{n} \sum_{j=1}^{n} d_{kl} \frac{L_{kl}}{\tau_{kl}},
$$

subject to

$$
\sum_{i=1}^{n} XARR_{ik} = 1, \quad k = 1, \ldots, n, \quad \text{(3)}
$$

$$
\sum_{k=1}^{n} XARR_{ik} = 1, \quad i = 1, \ldots, n, \quad \text{(4)}
$$

$$
\sum_{j=1}^{n} XDEP_{jl} = 1, \quad l = 1, \ldots, n, \quad \text{(5)}
$$

$$
\sum_{l=1}^{n} XDEP_{jl} = 1, \quad j = 1, \ldots, n, \quad \text{(6)}
$$

$$
XARR_{ik} \in (0, 1); \quad XDEP_{jl} \in (0, 1). \quad \text{(7)}
$$

Here $t_{arr,i}$ and $t_{dep,j}$ are predetermined times of possible arrivals and departures based on the infrastructural features of the airport, counted from the estimated time (the time central point in the fan of schedules), $d_{ij}$ is the matrix of the number of passengers wishing to transfer from line (flight) $i$ to line (flight) $j$, $D$ is the total number of passengers participating in the transfer process, $L_{ij}$ is the distance that passengers have to travel at the airport when transferring (moving to the airport and others mentioned earlier), $\tau_{ij}$ is the time spent by passengers at the airport during transfer. The time spent at the airport is calculated according to (2) as the sum of the times of possible arrivals $t_{arr,i}$ and $t_{dep,j}$ recalculated through the elements of two binary matrices $XARR_{ik}$ and $XDEP_{jl}$. The dimension of the matrices is equal to the number of transfer lines under consideration $n$. Constraints (3)–(6) describe the following conditions—the impossibility of simultaneous landing (departure) of aircraft and each aircraft can arrive only at one of the set of assigned arrival times. Likewise for shipments.

Additional conditions are that the stay time of the aircraft cannot be less than the time the aircraft is serviced before departure (depending on the type of aircraft)

$$
t_{arr,k} + t_{dep,k} \geq T_{serv} \quad \text{(8)}
$$

for all aircraft.
Criterion (1) is integral. It also seems useful to consider a more local criterion. When transferring, there are several flows of passengers—from aircraft to aircraft \( j_i = 1, \ldots, n \), \( j = 1, \ldots, n \). The total number of threads is \( n^2 - n \). To reduce the speed of passenger traffic, the minimax criterion seems to be an informative criterion. In the problem under consideration, it has the form

\[
\min_X \left( \max_Y \left( d_{kl} \frac{L_{kl}}{\tau_{kl}} \right) \right). \tag{9}
\]

The set \( X \) is feasible set of the variables \( XARR \) and \( XDEP \), the set \( Y \) is determined by the number of passenger flows. The expression in inner parentheses represents the flow rate. This characteristic is generally accepted in the analysis of transport systems and in the calculations of evacuation.

However, these problems are also difficult to solve, since the optimality criterion is represented by a nonlinear function of binary variables (variables in the denominator). Let us apply an alternative linear criterion—maximizing the total staying time of passengers at the airport

\[
\max \left( \sum_{k=1}^{n} \sum_{i=1}^{n} C_{ARR,ik} \ast XARR_{ik} + \sum_{l=1}^{n} \sum_{j=1}^{n} C_{DEP,jl} \ast XDEP_{jl} \right), \tag{10}
\]

where

\[
C_{ARR,ik} = t_{arr,i} \ast \sum_{l=1}^{n} d_{kl}, \tag{11}
\]

\[
C_{DEP,jl} = t_{dep,j} \ast \sum_{k=1}^{n} d_{kl}. \tag{12}
\]

In this variant, the general problem is solvable.

For the correct use of the above methodology, airport specialists will need to clarify the parameters: the length of the passengers’ path at the airport, approximately estimate the speed of passengers’ movement, provided there are no congestion or queues at all stages. They also need to determine in advance the possible time points of arrival and departure \( t_{arr,i} \) and \( t_{dep,j} \) based on the capabilities of the airport. The solution to the problem is to assign the time of arrival and departure of a specific flight (line) at specified time points, depending on the number of passengers who want to transfer.

3. Numerical experiments

Aviation regional interchange hubs located in the Siberian part of the Russian Federation were considered. Airlines operating in this region use the following types of aircraft: short-haul ERJ-170, CRJ-200, ATR-4-500, ATR72-500, RRJ-95 (passenger capacity 50–90 people), medium and long-rang B-737-800, A-321, B-767-300 (passenger capacity 170–300 people). The regulations for their service at airports are known and are reflected in the relevant documents. To detail the restrictions (8), the regulations for transit flights on domestic airlines were used.

Synchronization problem is implemented in Microsoft Excel. Typical sets of initial data and parameters are considered. Figure 1 shows the number of transit passengers at the airport when solving the classical synchronization problem—minimizing total staying time of passengers at the airport (red colour), the number of passengers at the airport while maximizing the total staying time of passengers at the airport (green colour) (criterion (10)). The abscissa shows the numbering of time blocks, each block is 15 minutes long. Comparison of the figures shows that the maximum number of passengers is observed in the central part fan of the arrival and departure, but in dynamics, maximizing the total time provides a lower intensity of passenger traffic.
Calculations of nonlinear criteria (1), (9) were carried out with the same data. The weighted average speed of passenger traffic (criterion (1)) decreases by about 20 percent. The values of the maximum intensity of passenger traffic (criterion (9) decreases by about 50 percent. In the classical problem of minimizing the total staying time, the maximum intensity of passenger traffic is about 10 times larger than the minimum intensity of passenger traffic. When maximizing the total staying time, the intensities of passenger traffic differ by a factor of 4–5.

Based on the results of the calculations, recommendations can be made on the refinement of the departure time from the source airports in order to ensure the required time and order of arrival at the regional transfer airport.

4. Conclusions

The proposed mathematical model of synchronization makes it possible to calculate the variant of slowing down passenger flows at transfer hubs. The slowdown of the flow of passengers is caused by the requirement for the safety of passengers in a pandemic, to maintain social distances at all stages of the stay of passengers at the transfer airport. Thus, it is proposed to implement one of the concepts of transport operation in a pandemic, especially to abandon the speed as a service in favor of safety. The total transfer time is limited by the model parameters and must be set in advance by the airport staff.

During normal periods of airport operation (without a pandemic), this mathematical model can work to speed up the transfer process using the generally accepted criterion—minimizing total staying time of passengers at the airport.

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