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Synchronization of the Timetable on Partially Overlapping Urban Transport Routes

Mirena TODOROVA
Todor Kableshkov University of Transport

Zlatin TRENDAFILOV
Todor Kableshkov University of Transport

Violina VELYOVA
Todor Kableshkov University of Transport

Abstract: In order to achieve competitive advantages of public transport over private vehicles, it is necessary to improve the quality of passenger service. This can be achieved by improving the regularity of the transportation, and reducing the waiting time at public transport stops. Each trip can be made with one or more vehicles, as well as with one or more modes of transport. A trip covers the time from departure from its starting point to arrival at the destination and a major element of the total travel time is waiting for a vehicle at the stop and namely it is the minimization of this time that is considered in the article/paper.A model has been developed for synchronizing timetables on different partially overlapping in a given section route lines, so as to reduce the interval between the arriving vehicles at the stop. The model includes passenger flow forecasting, by compiling an OD matrix for the considered route lines based on the partial use of the traditional four step demand modelling for travel planning. After determining the passenger flows, moving in the considered section of the route network, the existing timetables on route lines are synchronized under the criterion of a minimum of the total stay/waiting time of the passengers. The validation of the model is carried out by applying it to a part of the urban transport network of Sofia for two route lines, and the defined resistance function for the specific type of transport (bus transportation) is used to compile the O-D matrix

Keywords: O-D matrix, Synchronization of the tımetable, Waiting time, Urban transport, Overlapping routes

Introduction

Globally, we are moving forward to a new stage of "intermodal transport systems" for a balanced and coordinated use of all modes of transport and to make urban public transport systems attractive and efficient for citizens, who are encouraged to use them. This is also achieved by using soft and hard restrictions on car use to reduce chronic congestion and minimize damage to the urban environment.

Recently, in Bulgaria, the use of the services offered by public transport has been reduced. Therefore, various steps are being taken to improve the services offered by public transport, such as: the purchase of new buses, the introduction of innovative charging systems - the use of different subscription cards (for longer periods), tickets for a certain number of trips, for a certain time, which increases the comfort of travel and reduces costs when using public transport, synchronizing the timetables of the timetables on the different routes.

Literature Review

Regarding the articles and studies that are related to optimization of public transport schedules, it can be said that there are various methods to improve routes and travel time. In this part of the article, some of the most commonly used methods for optimization of overlapping routes on public transport lines are discussed and the statistics that consider these methods are described.

In article, Dragu et al., (2019), is shown two methods for distribution of trips between destinations - the Growth Factor Model and the Gravity Model. In the study is shown a case study using both methods, which are used for the developing of O-D Matrix, and in the conclusion of the article are described disadvantages of the both methods.

The paper, Jeongwook et al. (2019), analyses the overlapping origin–destination (O-D) pairs and the study aims according to the authors to enhance the efficiency of transit operations by collecting data from so called ‘smart card automatic fare collection system”. The knee points of travel demand are calculated using the Kneedle algorithm. For each of the bus routes in six districts with higher demand then the demand in Seoul, a demand-based overlap index is calculated on the basis of the overlapping O-D pairs, to evaluate the efficiency of bus operations.

In article, Mohammed & Jimi (2023), is given a comprehensive overview of the data sources, and different methods for estimating O-D models, such as: “General full-network O-D matrix estimation approach”, “Iterative proportional fitting algorithm”, “maximum entropy”, “maximum likelihood estimation”, “constrained generalized least squares”, “Bayesian estimation”, “Trip chaining”, “Validation of trip chaining assumptions and results”, “Spatial clustering”, “K-means clustering”, “Density-based spatial clustering”. The authors also wrote about recent developments in this field like: “Innovations in alighting and transfer inference algorithms”, “Real-time estimation”, etc.

The purpose of the article as authors presented in Philippe et al. (1984), is to clarify the route-choice problem. This was achieved by using passenger waiting times and mathematical formulas. A field-verified formulation between the variance and the mean of the bus headway and on two headway distribution families was made first, after that are developed probabilistic mathematical formulations. After that overlapping routes are categorized as slow or fast routes and also the number of passenger selecting each type of route is shown. According to the obtained research (Philippe et al., 1984), it was concluded that the behavior of passengers waiting at city bus stops should be further investigated.

In the article, Vovsha & Bekhor (1998), is presented a new link-nested logit model of route choice. The model is a particular case of discrete choice models and is generalized-extreme-value class model. The model is made to deliver results for overcoming the route overlapping problems in transportation and has a flexible correlation structure. Two equivalent mathematical programming forms are used to- deliver the model: a general Sheffi formulation and logit-based Fisk formulation and its generalization. The loading procedure of choise is stochastic network loading procedure. The authors are using numerical examples to compare the proposed model with other models. In statistics, the logit function is the quantile function (Todorova, 2019), associated with the standard logistic distribution. It has many applications in data analysis and is applied when the passenger flows are distributed. Mathematically, logit is the inverse of the standard logistic function.

Overlapping routes is one of the most common problems in analysis of travelling in urban areas (Hoogendoorn-Lanser et al., 2003). In this document (Hoogendoorn-Lanser, et al., 2003) overlapping routes are researched and instead of one factor for the volume ot the road are proposed different factors for subroutes to consider the differences in assessment in the overlapping. Logit model is used to show the influence of each of the factors. To examine the impact of individual subroute road size factors, multinomial logit, generalized nested logit, and models of basic logit path size models are used (Hoogendoorn-Lanser, et al., 2003). In the study in (Peterson, 2007) are shown different mathematical equations for time-dependent traffic models and time-independent O-D matrices.

Method

Each trip/journey can be made with one or more vehicles, as well as with one or more modes of transportation. The same has a starting point (origin) and an end (destination) point - a journey that starts from O and has a final destination- D. In this context, walking is also considered as a mode of transport. If the travel time from O-D is considered, it consists of three elements – walking to and from the bus stops, waiting at the stops and the travelled time with the vehicles. In order waiting time to be reduced the at the stops, the developed **a**

"Methodology for optimization of vehicle timetables on partially overlapping routes" can be used. The stages of the methodology are given in Fig.1.

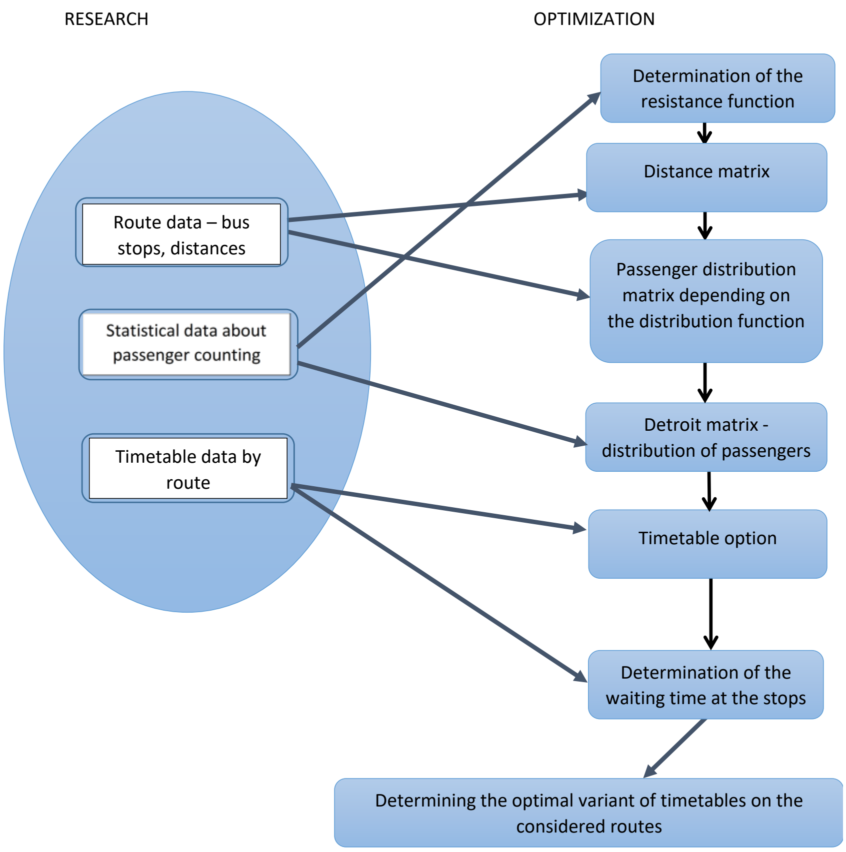

Figure 1. Stages of the "Methodology for optimization of vehicle timetables on partially overlapping routes"

In many sections of the transport network there is an overlap of two or more means of transport. If the overlap is large enough there is a passenger flow that travels exactly in that section. In this case, through the obtained O-D matrices of the individual lines of a route network, the vehicle schedule can be optimized, based on taking into account/ bearing in mind the correspondences along partially overlapping routes. Therefore, it is necessary to determine the routes that will be optimized and implement the following activities:

• Research - including the parameters of the routes themselves - stops, distances between them and determination of the general section on the basis of which the vehicle timetables will be replanned; data from studies of passenger flows for the type of transport considered and along the designated routes; as well as the current timetables on the considered routes.
• Optimization consisting of the following stages:

Determination of the Resistance Function

Passenger flows depend on various factors and are variable over time. In order to establish the upcoming changes in the directions, it is necessary periodically to be studied, as the received data should provide the opportunity for regular corrections of the transport options of the urban public transport so that it meets the constantly changing transport needs of the population.

The most widely used methods and models for determining the expected or realized passenger flows in mass urban transport are the various types of surveys among the population and physical censuses (tabular, ticket counting, chamber method, physical counting method, etc.) by routes or stops (Sarkar et al., 2017). In this way, the departures and arrivals for different stops are determined. However, there is still no clarity about the destination of the trips that start from a certain bus stop nor is it known where the trips generated for a particular bus stop come from, therefore it is necessary the trips, presented in this study area in the so-called origin-destination matrix or O-D-table (origin-destination matrix) **(**Kevin et al., 2011).

Therefore, the purpose of the distribution model is to determine the O-D table for a given forecast year. One approach to determining the distribution is to use the the resistance level/sustainability level of the travels/trips or the resistance between the zones as a measure by which to allocate trips in the first O-D table. The effort or resistance to undertaking a journey is called travel resistance (Todorova, 2019). When it comes to public transport, where the use of travel cards is a widespread case, it is obvious that this resistance can only be expressed in terms of travel time or distance. It is intuitively clear (and empirical research shows) that the number of trips to a destination decreases as the distance (or rather road resistance) to that destination increases. This effect of road resistance on trip distribution is expressed by the deterrence function $P(L_{ij})$.

Depending on the organization of urban transport, on the centers of attraction depending on the urban plan, depending on the personal characteristics of travelers and on the mode of transport, different deterrent functions are used, but most often exponential indicators or mixed functions are used. Therefore, such a function must be derived for city or town and a study should be conducted and derived.

Creating a distance matrix - for each considered route line, such a matrix is compiled and depending on the distances between the stops, the matrix is filled with number of columns and data equal to the number of stops on the considered route line.

Creating an initial matrix of passenger flows – a matrix is filled with elements obtained on the basis of the distances between them and using the derived resistance function for the settlement.

Distribution of passengers along the routes - a different "growth factor models" can be used for the urban transport routes (Todorova et al., 2018).

This is done using an initial passenger flow matrix and passenger count data on the route under consideration. After a passenger count has been carried out at the stops on a given public transport line and the number of departures and arrivals has been determined, the next step is to determine the distribution of the future journeys between the stops. The methods for the distribution of trips /distribution/ are used, stopping to use the Detroit method (Novačko 2014), in which, in addition to the growth factor for individual stops, the generalized growth factor is also taken into account. All this can be expressed mathematically as follows:

$$T_{ij}^{k} = T_{ij}^{k-1}.\left(\frac{F_i^{k-1} * F_j^{k-1}}{F^0}\right) \quad (1)$$

$$F^0 = \frac{P^*}{P^0} \quad (2),$$

where:
P^0 – volume of the actual correspondences
P^* – volume of estimated correspondences
F_i^0 ; F_j^0 – growth factors
T_{ij}^0, T_{ij}^1, T_{ij}^* – actual, estimated and estimated correspondences

For a comparison between the estimated and calculated correspondences, one resorts to approximate methodological solutions, and then ratio (1) takes the form:

$$F_i^{(k-1)} = O_i / \sum_i T_{ij}^{(k-1)}$$
$$F_j^{(k-1)} = D_j / \sum_i T_{ij}^{(k-1)}$$

where:
T_{ij}^k - future flow ij

$T_{ij}^{(k-1)}$ – current flow ij
O_i–future generated flow at stop i
$\sum_i T_{ij}^{(k-1)}$ - current generated flow at stop i

D_j – future (wheigthed center) attraction of stop j

$\sum_i T_{ij}^{(k-1)}$ - current attraction of stop j

k- the iteration number.

Detroit's method is not difficult to read and allows to determine predictions with great accuracy. This model uses an iterative process to approach the final solution. The results of the computations of each iteration constitute the input data for the next. This process is carried out until an approximation is obtained between the predetermined values of boarded - disembarked passengers and the size of the correspondences obtained as a result of the calculations for a given stop / that is, the coefficients F_i^K, F_j^K tend to approximate to 1 (3).

$$F^0 \to 1, F_i^K \to 1, F_j^K \to 1 \qquad (3)$$

Based on the obtained distributions, the correspondences between the stops of the overlapping routes and the size of the passenger flows are obtained. Determination of timetable options for the purpose of optimization - the real timetables of the vehicles are considered and an optimization strategy is determined depending on the frequency of the vehicles - do we have a main line with a small interval between the vehicles (Todorova et al. 2017) and others with a large interval or we have lines with close vehicle intervals.

The Waiting Time for the Vehicle at a Stop

The waiting time for the vehicle starts from the moment the passenger arrives at the stop until the moment he gets on the vehicle. Obviously, this time will be a function of the movement interval, varying within the limits 0<=$\boldsymbol{t}_{\mathbf{waiting,min}} =< \boldsymbol{I}_{movement}$. Taking into account the random nature of the arrival of the passengers at the stop and the arrival of the vehicle, where the movement intervals are random variables varying from 0 to 2 $\boldsymbol{I}_{movement}$, the waiting time of the vehicle is:

$$\boldsymbol{t}_{\mathbf{waiting}} = \frac{\boldsymbol{I}_{\mathbf{movement}}}{\mathbf{2}} (1 + \vartheta(t)^2) \qquad (4)$$

$\vartheta(t)$– – coefficient of variation of real movement intervals.

Taking into account that the time that the passenger spends waiting for a vehicle at a bus stop of mass urban transport, represents 20% of the total travel time, the reduction of this component appears to be a reserve, not only for reducing the "resistance" of movement, but also for attracting new potential passengers. In order to determine the size of the passenger hours for waiting for a vehicle, it is necessary to determine the size of the passenger flow for the given traffic interval and the corresponding waiting time.

$$H_{ijm} = \sum_m (\mathrm{N}_{\text{pasenger flow, m}} * t^m_{waiting,ij}) \qquad (5)$$

where:

$\sum_m \mathrm{N}_{\text{pasenger flow, m}}$ - the passenger flow for a time interval m=1,M moving along a route between stops ij;

$t_{waiting}{}^{m}_{ij}$- the time for the passenger to wait for the vehicle for a time interval k moving along a route between stops ij;

Optimization of timetables – the criterion for optimization is minimization of passenger hours waiting for the vehicles at the stops. For the different variants, the average interval between the vehicles arriving at the stop, their root mean square deviation, the coefficient of variation of the arrival interval and hence the magnitude of the vehicle waiting time are determined. Using the determined passenger flow for the given time range, the passenger waiting hours for the train are also calculated. The variant with the minimum value of this parameter gives us the optimal schedule for the given lines. If we have another line with a smaller passenger flow, it is also included in the variant formation.

$$\sum_m H\mathrm{ijm} \to \min \qquad (6)$$

Case Study

Models for non-modal distribution (moving with one mode of transport) are considered. Two routes are presented with buses are overlaping each other within 8 bus stops for a length of 4.5 km. One line is number 11 and the route is double radial with a total length of 16 km, and the other route is 404 - with a radial route and a route length of 13 km (the route diagram is given in Fig. 2).

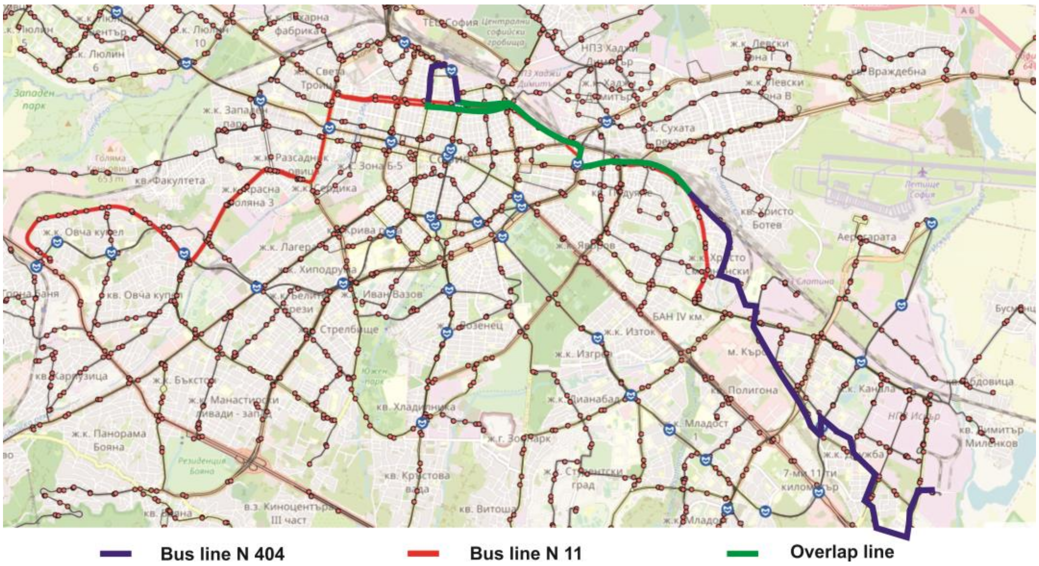

Figure 2. Routes of the considered lines 11 and 404

A study was made of the passenger flows on selected lines of Sofia's public transport. In this case, the physical counting method is used, through counters at the stops, and the number of passengers who boarded and disembarked is determined. Figure 3 shows the count of one of the directions on route line 11, while there are similar data for the opposite direction and for bus line 404.

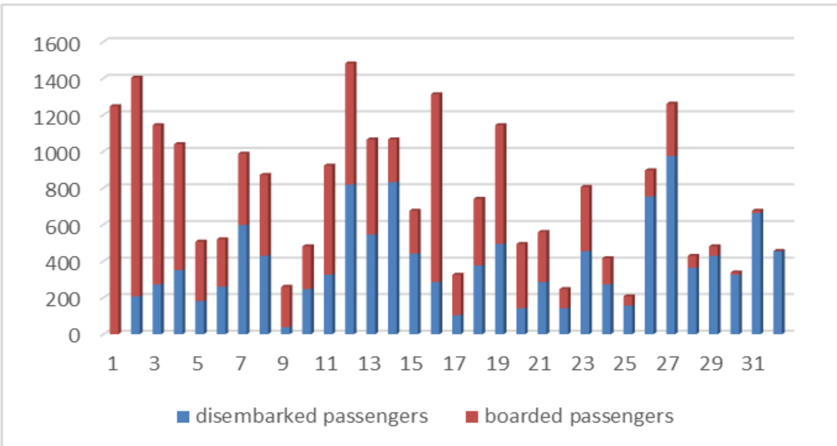

Figure 3. Number of boarded and disembarked passengers through route number 11

In order to determine the passengers moving only in the overlap section of the two lines, several matrices are compiled: first a matrix of the distances between stops, then a matrix of the generated passengers using the resistance function and the distances between stops. In this case, the derived resistance function is used from a study done on bus lines in the territory of Sofia and presented in (Todorova, 2019). It has the form:

$$P(L_{ij}) = d + a.e^{b.L_{ij}}.L_{ij}^{c} \qquad (7)$$

where:

Lij – is the distance traveled by the passenger from stop i, where he gets on, to stop j, where he gets off;

a, b, c, d - are coefficients of the function and are a=52.77; b= -0.82; c=1.31 and d =2.

In the resulting matrix of generated passengers, the Detroit method is applied and only the passenger flows for each direction and line are obtained separately. Using these data, the combined passenger flows for each direction are obtained, the distribution of which by time ranges is given in Figure 4.

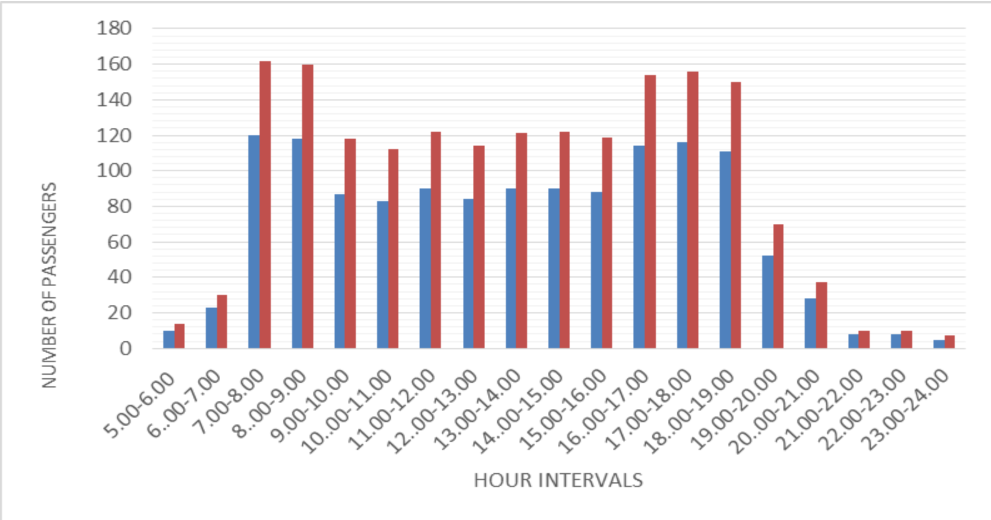

Figure 4. Number of passengers with destinations in the overlap section per day

The intervals between vehicles moving on the two route lines are almost with the same duration of time, differing in given time ranges by a minute or two. For this reason, a change in the timetable will be proposed, due to a recalculation of the movement intervals between the means of transport, based on their arrival at a given stop, regardless of the number of the line.

The determination of the new vehicle movement intervals is based on the obtained average intervals in each of the stops between the means of transport serving the two considered lines for the time ranges from 5 to 24 hours per hour. When determining the waiting time of the vehicle, data on the delay along the entire course (average delay) is used, and this delay is probabilistically distributed for each of the time intervals and participates in determining the coefficient of variation of the real intervals of movement.

Results and Discussion

The results for determining the optimization criterion passenger-hours waiting for a vehicle in one of the directions are given for the real traffic schedule in Figure 5, and for the proposed schedule in Figure 6.

time range	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
m	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
$I_{movement}$	7.800	8.714	6.300	6.778	7.857	9.714	8.250	8.143	8.000	7.429	8.857	7.000	6.222	7.000	7.222	10.000	13.500	13.500	16.500
$\vartheta(t)$	0.264	0.16	0.2	0.385	0.247	0.23	0.300233	0.299	0.308	0.338	0.312	0.2197	0.348	0.27	0.247	0.143	0.117	0.132	0.11
$t_{waiting}$	4.172	4.469	3.276	3.891	4.168	5.114	4.497	4.435	4.379	4.139	4.860	3.669	3.488	3.755	3.831	5.102	6.842	6.868	8.350
$N_{passenger,m}$	14	30	162	160	118	112	122	114	121	122	119	154	156	150	70	37	10	10	7
H_{ijm}	58.405	134.061	530.712	622.593	491.853	572.778	548.613	505.638	529.914	504.912	578.300	565.017	544.109	563.273	268.199	188.783	68.424	68.676	58.449
														SUM of Passenger-hours waiting time for the vehicle					123.378

Figure 5. Waiting for a vehicle measured in passenger-hours in a real schedule

time range	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
m	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
$I_{movement}$	8	9	6	7	8	10	8	8	8	7	9	7	6	7	7	10	13	13	17
$\vartheta(t)$	0.1	0.11	0.21	0.23	0.18	0.23	0.26	0.25	0.22	0.2	0.21	0.18	0.21	0.23	0.14	0.11	0.1	0.1	0.1
$t_{waiting}$	4.04	4.554	3.132	3.685	4.130	5.265	4.270	4.250	4.194	3.640	4.698	3.613	3.132	3.685	3.569	5.061	6.565	6.565	8.585
$N_{passenger,m}$	14	30	162	160	118	112	122	114	121	122	119	154	156	150	70	37	10	10	7
H_{ijm}	56.560	136.634	507.433	589.624	487.293	589.624	520.989	484.500	507.426	444.080	559.116	556.464	488.639	552.773	249.802	187.239	65.650	65.650	60.095
														SUM of Passenger-hours waiting time for the vehicle					118.493

Figure 6. Waiting for a vehicle measured in passenger-hours under the new proposed schedule

As found for this direction, the total waiting time in passenger-hours per vehicle for the new timetable variant saves 4 hours and 53 minutes of passenger-hours per day.

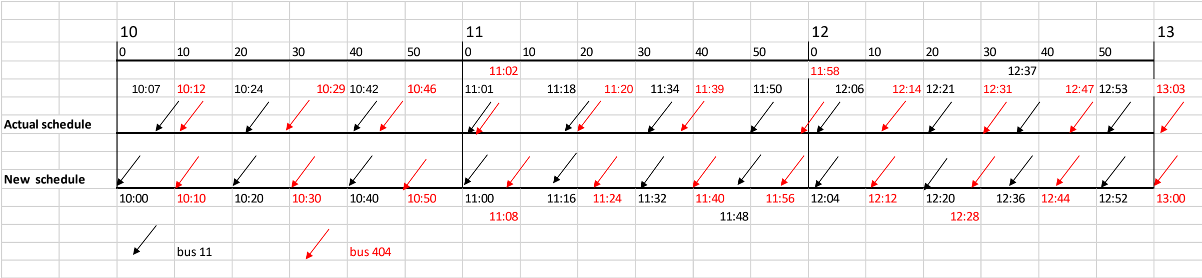

Figure 7. Schedules for the movement of vehicles for the interval from 10 a.m. to 1 p.m. for the first general stop in one of the directions.

Figure 7 shows the change in the traffic schedule of the vehicles on the two lines for 3 intervals/ ranges of hours. This change will result in a reduction of 8,50 passenger-hours waiting time per vehicle at these 8 stops per day for both directions, or one business day.

Conclusion

The developed method includes a sequence of steps that are in the field of passenger flow forecasting and methods for optimizing the organization of vehicle movement in urban transport. In order to be able to use the method, it is necessary to have a preliminary study of passenger flows along the studied lines.The article examines lines on which the interval of movement of the vehicles included in the schedule that are almost with the same duration of time and the approach to determine the new schedule is based on their even distribution using their average value by hourly periods and the coefficient of variation of the real intervals of movement. The obtained results show the possibility of applying the method in similar cases, because the reduction in passenger hours waiting time for vehicles is significant, as well as for the optimization of vehicle schedules.

Recommendations

The results of the applied method should be provided to the urban mobility centre, which manages urban transport in Sofia.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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Author Information

Mirena Todorova
Todor Kableshkov University of Transport
Address: 1574 Sofia, 158 Geo Milev Str., Bulgaria
Contact e-mail: mtodorova@*vtu.bg*

Zlatin Trendafilov
Todor Kableshkov University of Transport
Address: 1574 Sofia, 158 Geo Milev Str, Bulgaria

Violina Velyova
Todor Kableshkov University of Transport
Address1574 Sofia, 158 Geo Milev Str., Bulgaria

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