

Key words: combined transportation mode; inter-stop communication matrix; traffic interval; capacity use coefficient; unproductive transportation

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DETERMINATION OF RATIONAL PARAMETERS FOR URBAN BUS ROUTE WITH COMBINED OPERATING MODE

Summary. The paper considers the problems concerning the improvement of passenger transportation process at the expense of the combined operating mode implementation. Efficiency criteria to implement the mixed conveyance forms have been formulated. An extensive approach to determine stopping points, involved in a high-speed route, has been proposed. An economic and mathematical model has been developed. The model makes it possible to study and determine both expediency and rational parameters concerning the implementation of the mixed high-speed conveyance forms. A structure of the integrated efficiency index has been proposed helping select the best approach, and involving the basic economic, technological, and social indices. The modeling outcomes as well as performance efficiency, resulting from the implementation of a high-speed conveyance in the context of an urban route, have been represented.

1. INTRODUCTION

Currently, the national economy of Ukraine is in the process of its transition from administrative management to economic ones. Taking into account the consequences of financial crisis, annexation of the Crimea, and military intervention in Donetsk and Luhansk Regions, the transition process is followed by a number of negative events including significant decline in production, capital assets wear, inflation, etc. Even with the certain budgetary aid, reforming of property and productive relations, reflecting the efficiency of urban motor transport, a level of economic indices, remains low. The fact results in the loss ratio, and low profitability of the majority of automobile operating companies (AOCs) [1].

The situation puts forward a task to identify and use internal reserves of AOCs relying upon the improvement of passenger transportation process [2]. Identification of the reserves, implementation of their potential with the consideration of a new economic behaviour of AOCs as for the marketing, production, and fiscal policies is one of the most important tendencies to advance economic, technological, and social indices of public transport operation. Automobile operating companies should be interested in the useful effect of their activities which will favour the development of a less expensive transport infrastructure. In this case, the decreased transportation expenses are the factor to raise real earnings [3]. Hence, many AOCs face the necessity to determine such route conveyance variations that will result in minimum expenses and maximum efficiency of road transport vehicles while involving the necessity to convey passengers with the stipulated quality indices.

The abovementioned problems may be solved if high-speed (i.e. express, and semi-express) conveyance system is implemented including determination of mixed forms and modes that would minimize unprofitable operation of road transport vehicles with no service quality deterioration. Its rational management, making it possible to accelerate conveyance process and save passenger time, is quite important for the level of road transport vehicles use as well as for the level of passenger

service [4-8]. It should also be noted that implementation of such combined operating modes for buses within urban routes helps achieve the aforementioned economic and social effects, with no increase in the number of buses. Conversely, if adequate structure of passenger traffic on a certain route is available, it becomes possible to reduce bus number without any service loss. That can be done owing to the decreased running time in turn factoring into bus turnover and into the increased carrying capacity of the route correspondingly [9-11]. As high-speed buses and express ones have fewer stops during their routes, they brake and accelerate rarely which favour the decreased depreciation of the vehicles as well as the reduced expenditures connected with motor fuels economy, current repair and maintenance of the bus fleet, and decreased vehicle emissions [12-13].

2. STATE OF THE ART

Selection of vehicle operating mode is one of the most problems while improving traffic process as it effects immediately the process quality as well as its prime cost. From the technological viewpoint, following basic operating modes of passenger automobile transport can be singled out: high-speed, express, semi-express, condensed, and operating mode of a route taxi [8-9]. It is expedient to develop combined operating modes for urban passenger transport to be a combination of a customary mode and express (high-speed) one. In this context, the express (high-speed) mode may be implemented as an independent route. The main distinction between combined operating mode and customary one is as follows: in the context of a combined mode, fewer than all route buses have to keep all stops. In this context, the buses, having their stops at each roadside station, depend on the operating mode only thus characterizing correctly the combined operating mode as for the bus stop [14]. Despite the listed advantages, such traffic variations are not popular now. First of all, the variations have no rather accurate and reliable substantiation techniques.

It should be noted that most available methods to implement the combined operating mode for urban routes were developed in the 1970s-1990s before changes in transport economic conditions. Thus, they cannot take into consideration self-interest of AOCs in financial results of their activities. Paper [10] performs detailed analysis of the methods listing their application areas as well as advantages and disadvantages [10].

Paper [5] proposes a technique to implement mode selection relying upon enumeration of possibilities concerning conveyance management in terms of a certain route. Minimum conveyance velocity, maximum passenger turnover value at stops, and maximum traffic interval are taken as limitations. The idea to improve service quality with no traffic deterioration has been taken as a criterion. However, as practices show, implementation of such techniques results in the development of operating modes that cannot meet the requirements of passengers in full.

Findings in [16] make it possible to solve a problem concerning determination of an output set of stopping points for further enumeration of possibilities as well as substantiation of a hypothesis to help passengers take their choice as for the transportation mode. The authors believe that the proposed approaches as to passenger flows separation may result in irrational distribution of buses among routes; moreover, they are very labour intensive, and involve unnecessary calculation operations.

Paper [17] specifies application area of route taxis and has determined a traffic management technique for urban passenger transport, making it possible to select rational parameters of route conveyance with combined operating mode taking into consideration service level and prime cost of the transportations. Disadvantage of the paper is as follows: taxi routes, where vehicles which passenger capacity is up to 30 people, are considered as application area of the proposed mathematical model.

The authors suppose that optimization technique, proposed by paper [14], is the most popular one today as it uses passenger turnover within stopping points of a route as output data. As for the problem to determine combined service in terms of routes, it is concerned as an extremum one using overall passenger time consumption as the efficiency criterion. A variable characterizing the bus share, having their stops at each roadside station of the route, is the optimization parameter to be determined. The main disadvantage of the technique is that it cannot involve economic indices of AOC performances.

Hence, the aforementioned studies and approaches at the most may be applied for aggregate calculation variants or approximate ones. Moreover, lack of a common strategy helping determine rational parameters for the combined conveyances can explain their minor specific weight being no more than 5% of total number of urban routes.

Taking into consideration critical analysis of the listed techniques, it is possible to state that the objective is to develop both strategy and economic and mathematical model making it possible to study and determine rather reliably the expediency as well as rational parameters of the combined rapid conveyance forms implementation in terms of a certain urban route with the help of the selected optimum criteria. The calculation should identify such parameters as traffic volume, standard traffic rates depending upon services, arrangement of stopping points, a value of unproductive transportation, saved passenger time, and potential economic effect. It should also be noted that in the context of each service type, it is necessary to determine corresponding passenger traffic flow, standard rates per run, and the number of vehicles to be used. In the process, determination of adequate passenger traffic flows for each service is a multivariant problem, whose solution results in obtaining of the indices evaluating the transportation within certain route as well as the road transport vehicles efficiency. Hence, to evaluate the modeling results, it is also required to develop a structure of a complex efficiency index that would involve economic, technological, and social components of passenger traffic flow while implementing the combined operating mode.

3. DATA FOR THE STUDY

Decrease of inefficient bus operation is the basic technological effect resulting from the combined operating mode implementation:

$$W_N = \sum P_{specified}^i - \sum P_{actual}^i \tag{1}$$

where $\sum P_{specified}^i$ is total transportation specified in terms of each i^{th} service type, pas.·km; $\sum P_{actual}^i$ is total actual transportation in terms of each i^{th} service type, pas.·km.

A diagram of passenger flow within a route, represented in Fig. 1, is characterized by the availability of significant communications between end stops and in its central share.

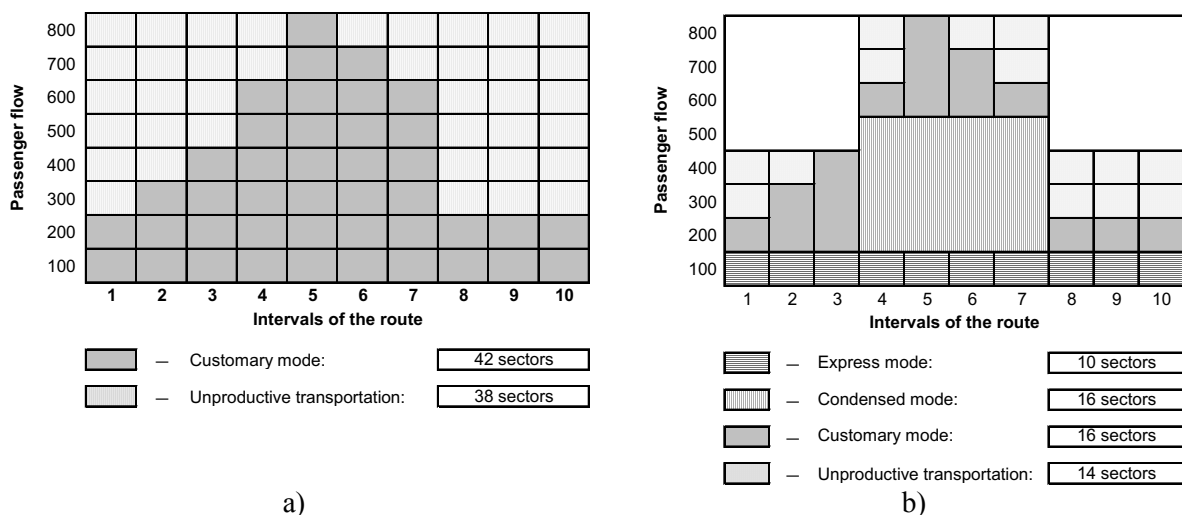


Fig. 1. Demonstration of principal possibility to reduce unproductive transportation at the expense of the combined traffic: a) customary mode and b) combined mode

If buses operate in a customary (i.e. stop-by-stop) mode (Fig. 1, a) then it will be characterized by following indices: $\sum P_{specified}^i = 80$ «nominal units», $\sum P_{actual}^i = 42$ «nominal units», and $W_N = 38$ «nominal units»; efficiency of such a system is $42/80=0.53$.

In turn, customary traffic, supplemented by express traffic and condensed one in terms of 4, 5, 6, and 7 routes (Fig. 2, a) will make it possible to reduce W_N down to 14 «nominal units» while improving the system operation up to $(10+16+16)/(10+16+16+14)=0.75$.

Thus, neither express traffic nor condensed one can affect passenger route or the number of their transportations; hence, it cannot introduce changes in average trip distance or the number of the passengers transported. However, that varies such indices of transportation process as total run of road transport vehicles, their fullness, the number of buses and their efficiency, operational expenses, traffic prime cost, total passenger time consumed including time for transportation and waiting time.

3.1. Substantiating the expediency to implement the transportation types

The expediency to implement one or another transportation type within routes depends upon coefficients of passenger flow unevenness [18-20]. Passenger turnover coefficient and unevenness coefficient within the route sectors are among them. Passenger turnover coefficient characterizes passenger turnover in a passenger compartment during a run; it is determined by means of route length L_R – average trip distance of a passenger l_{av} ratio [8-9, 14]:

$$\eta_{turn} = \frac{L_R}{l_{av}}, \quad (2)$$

It is typical for express mode that $l_{av} = L_R$; thus, $\eta_{turn} = 1$. Alternatively, in terms of a customary mode, average passenger trip is equal to a section length; hence, it is possible to assume that $l_{av} \cong \overline{l_{run}}$, and $\eta_{turn} \cong n$, where n is the number of sections within a route. It follows that:

$$\eta_{turn} = 1 \div n. \quad (3)$$

Thus, the more $\eta_{turn} \rightarrow 1$ is, the greater number of passenger use stopless route, and the more efficient express mode is.

Unevenness coefficient within $\eta_{unev/sec}$ route sectors is determined by means of ratio between maximum passenger flow H_{max} (within the densest section of the route) and its average value H_{av} in the context of each section of the route [8-9, 14]:

$$\eta_{unev/sec} = \frac{H_{max}}{H_{av}}. \quad (4)$$

Express mode (if $\eta_{turn} = 1$) is characterized by no passenger flow variations in terms of route sectors; hence, $H_{max} = H_{av}$, and $\eta_{unev/sec} = 1$. Significant variations in passenger flow in terms of the route sectors should involve the implementation of a condensed mode. In this context (if $(H_{max} \gg H_{av})$), it is possible to assume that $H_{av} \cong H_{max} / n$. Then $\eta_{unev/sec} = H_{max} / H_{av} \cong n$. It follows that:

$$\eta_{unev/sec} = 1 \div n. \quad (5)$$

Right boundary of a section $[1 \div n]$ in (3) and (5) is floating; it depends on the number of sectors within a run to be not always convenient while analyzing a passenger flow. Hence, it is expedient to introduce standardized coefficients (k_{turn} , $k_{unev/sec}$) as $1/\eta$ ratio for the abovementioned unevenness coefficients. Then:

$$k_{turn} = 1/\eta_{turn}; \quad k_{turn} \in (0...1]. \quad (6)$$

$$k_{unev/sec} = 1/\eta_{unev/sec}; \quad k_{unev/sec} \in (0 \div 1]. \quad (7)$$

The obtained dependences help compile a table of correspondence between boundary values of the standardized coefficients (k_{turn} , $k_{unev/sec}$) and transportation modes matching them (Table 1).

Table 1

Application area of different transportation modes

k_{turn} value	$k_{unev/sec}$ value	Transportation mode
$k_{turn} = 0.5...1$	$k_{unev/sec} = 0.5...1$	express mode
$k_{turn} = 0.5...1$	$k_{unev/sec} = 0...0.5$	customary mode
$k_{turn} = 0...0.5$	$k_{unev/sec} = 0...0.5$	condensed mode
$k_{turn} = 0...0.5$	$k_{unev/sec} = 0.5...1$	condensed and express mode

3.2. Efficiency criteria to implement the combined operating modes

Two key parties take part in the transportation process within urban routes: automobile operating companies and passengers; their interests are not always reconciled [14]. Following measures may be a compromise solution. Objectives of the measures are as follows:

- the improvement of AOCs performance with no passenger service deterioration and
- the improvement of passenger service with no deterioration in economic indices.

Such a multicriteria approach makes it possible to involve multidirectional nature of the transportation process objectives, and antagonism between its components (both economic and social). Successful definition of any extremum problem and its solution depends heavily upon the adequate selection of efficiency criterion [21-22]. In this context, the selected efficiency criterion should take into consideration urban passenger transport management, and available technical and economic performance; evaluate the transport facilities functioning; and accept evaluation of the comparison variations while being rather informative.

The authors propose take a value of unproductive operation of road transport vehicles $W_N(1)$ as the key index of AOC performance (it determines bus efficiency as well as transportation process prime cost); a value, being equal to total passenger time consumed including time for transportation and waiting time, is considered to be the key index of transportation service. Thus, in general, the authors propose to formulate a potential approach to solve a problem concerning determination of rational parameters of the combined mode with the help of following models taking into consideration interests of AOCs (8) and passengers (9) respectively:

$$W_N \geq 0; \quad A_{before} > A_{after} = \sum A_i; \quad \gamma_i \in [\gamma_{min} \div \gamma_{max}]; \quad \min A^{CUST} = t_{cir} / I_{max} \tag{8}$$

$$\sum T_{before} > \sum T_{after}; \quad A_{before} = A_{after} = \sum A_i; \quad \gamma_i \in [\gamma_{min} \div \gamma_{max}]; \quad \min A^{CUST} = t_{cir} / I_{max}; \tag{9}$$

where A_{before} , and A_{after} are the number of buses before implementation of different transportation types and after it respectively; A_i is the number of buses of i^{th} transportation type; $\sum T_{before}$, and $\sum T_{after}$ are total passenger time consumed including time for transportation and waiting time before implementation of different transportation types and after it respectively; $\min A^{CUST}$ is minimum permissible number of buses for customary transportation within a route; I_{max} is maximum permissible interval; γ_i is a coefficient to use capacity of i^{th} transportation type, and $[\gamma_{min} \div \gamma_{max}]$ are its minimum and maximum respectively; t_{cir} is bus circulation time.

In the context of new economic performance of AOC, variation of model (8) is the best one, as minimization of unproductive transportation results in the reduced transportation cost; if effective tariff system is applied, it may also result in the improved profitability of automobile operating companies.

3.3. Calculating a matrix of inter-stop communications

Implementation of the combined transportation modes within complex routes is supported by the dedicated software relying upon analysis of mathematical models of passenger flows structure and route parameters [4, 8, and 12]. It is supposed that combinatorial procedures [9 and 14] are the most advanced technique for the problem optimum solution. The procedures are successive formation and comparative analysis of the problem variants; they differ in certain combination of output parameters.

In the context of abovementioned models (8) and (9), a matrix of inter-stop communications (ISCs) should be applied as the basis for analysis; its elements determine the use of the simplest transportation types. Table 2 demonstrates generalized view of the ISC structure. For instance, $\{K_{1n}, K_{n1}\}$ elements are passenger communications for whom express is the most appropriate transportation type as they run from end of the route to its end. On the other hand, such diagonal elements as $\{K_{12}, K_{23}, K_{34} \dots K_{(n-1)n}\}$ and $\{K_{21}, K_{32}, K_{43} \dots K_{n(n-1)}\}$ are communications of passengers being interested in the customary transportation type. For all other elements of the matrix, express transportation type is the most effective one in terms of both the whole route and its certain segments. With the use of a set of combinations of stopping points of express transportation types as well as variations of road transport vehicles use, rational alternative may be applied providing either minimum of unproductive transportation operations of the vehicles or minimum of time consumed by passengers. However, many researchers believe that the necessity to obtain information concerning inter-stop communications within a route is the key disadvantage of the combinatory technique making it more expensive and complicated.

Table 2

Generalized view of a structure of inter-stop communications matrix

Stopping point	1	2	3	4	...	(n-1)	n
1		K_{12}	K_{13}	K_{14}	...	$K_{1(n-1)}$	K_{1n}
2	K_{21}		K_{23}	K_{24}	...	$K_{2(n-1)}$	K_{2n}
...
(n-1)	$K_{(n-1)1}$	$K_{(n-1)2}$	$K_{(n-1)3}$	$K_{(n-1)4}$...		$K_{(n-1)n}$
n	K_{n1}	K_{n2}	K_{n3}	K_{n4}	...	$K_{n(n-1)}$	

In fact, ISC obtaining with the help of passenger flows survey (i.e. polling or ticketing) is quite a complicated time consuming and expensive problem. It should be noted that analytical techniques are available [14] making it possible to determine ISCs with 5-7% error using data on passenger turnover within stopping points. Elements of the matrix K_{ij} are identified according to the dependences:

$$K_{ij} = \frac{B_j \cdot C_{ij}}{H_{(j-1)j}}, \tag{10}$$

where B_j is the number of passengers who left a bus at j^{th} stopping point; C_{ij} is the number of passengers who got into a bus at i^{th} stopping point and left it at j^{th} stopping point and other ones; and H_{j-1} is a bus fullness within a run between $(j-1)$ and j^{th} stopping points.

The number of passengers who travelled at least one run of the route:

$$C_{i(i+1)} = 3_i; \quad C_{ij} = C_{i(j-1)} - K_{i(j-1)}. \tag{11}$$

It should be noted that the majority of bus routes in cities consist of 30 stopping points on average; thus, the number of K_{ij} matrix elements is $30 \cdot 30 - 30 = 435$ values for one driving direction. Taking into consideration the necessity in additional calculation of C_{ij} coefficients, overall computations may achieve 870 values. Automated ISC calculations according to (10-11) are complicated by the fact that the current iteration should involve the results of a previous one. To simplify the calculations, the

authors have developed an algorithm of integral *Microsoft Excel* consumer function helping perform the required calculations, avoiding coming back to a previous iteration. The algorithm has been developed within such a software environment as *Microsoft Visual Basic*. Fig. 2 demonstrates flow diagram of the algorithm as well as a code of its implementation within *Microsoft Visual Basic* software environment. Following parameters are the developed consumer function arguments: P_i is the number of passengers who got into a bus at i^{th} stopping point; i is a line number within *Microsoft Excel* sheet where C_{ij} value is being calculated; j_0 and j_t are numbers of a start column and terminal column within *Microsoft Excel* sheet where the calculated K_{ij} values are located; and N_{st} is the number of a stopping bus where C_{ij} is being calculated.

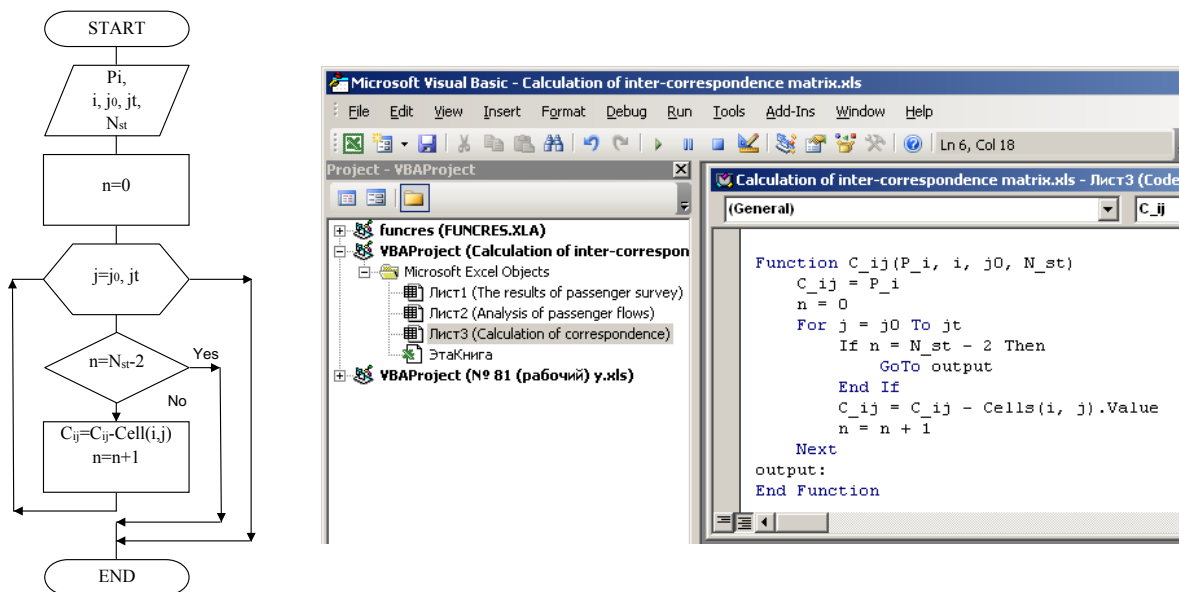


Fig. 2. Flow diagram of an algorithm to calculate C_{ij} coefficients and software for its implementation within *Microsoft Visual Basic* environment

3.4. Determination of the stopping points involved by the express route

Determination of stopping points to become integral part of the express route is one of the most important problems while implementing combined transportation types. Since the express transportation idea is that not all buses have each stop, it can be represented in the form of logic (Boolean) vector whose elements may acquire 1 or 0 values:

$$Z = \{ \lambda_1, \lambda_2, \lambda_3 \dots \lambda_j \dots \lambda_n \}, \tag{12}$$

where $\lambda_j=1$ if j^{th} stopping point is involved in the express route; and $\lambda_j=0$ if j^{th} stopping point is not involved.

Both initial and terminal stopping points of the basic route should be involved in the high-speed run; thus $\lambda_1=\lambda_n=1$. As for the set of other stops $\{ \lambda_2 \dots \lambda_{n-1} \}$, it is necessary to apply empiric condition of expediency to exclude a stop by express bus at j^{th} stopping point of the basic route [14]. The authors believe this very condition is that one taking into consideration specific nature of passenger flow within a route making it possible to obtain such combinations (1) which will help implementing the most efficient variants of the combined operation mode for both passengers and AOCs:

$$\frac{F_j}{Q_j} > I, \tag{13}$$

where F_j is the number of passengers going by a j^{th} stopping point; Q_j is passenger turnover between j^{th} stopping point and a stop; and I is bus interval in the context of a customary transportation mode.

Key advantage of empiric condition (13) is the fact that during a day, bus interval varies significantly: from I in the morning rush hour to $2I-3I$ in the inter-peak period. Thus, while performing study [23], authors have proposed an expanded approach to determine vector (12) elements. Hence, Fig. 3 demonstrates the results of calculation (13) for urban route where the combined transportation mode is planned to be implemented with the use of a high-speed traffic; in the context of the route, bus interval is 5 minutes during morning rush hour, and 15 minutes during inter-peak period.

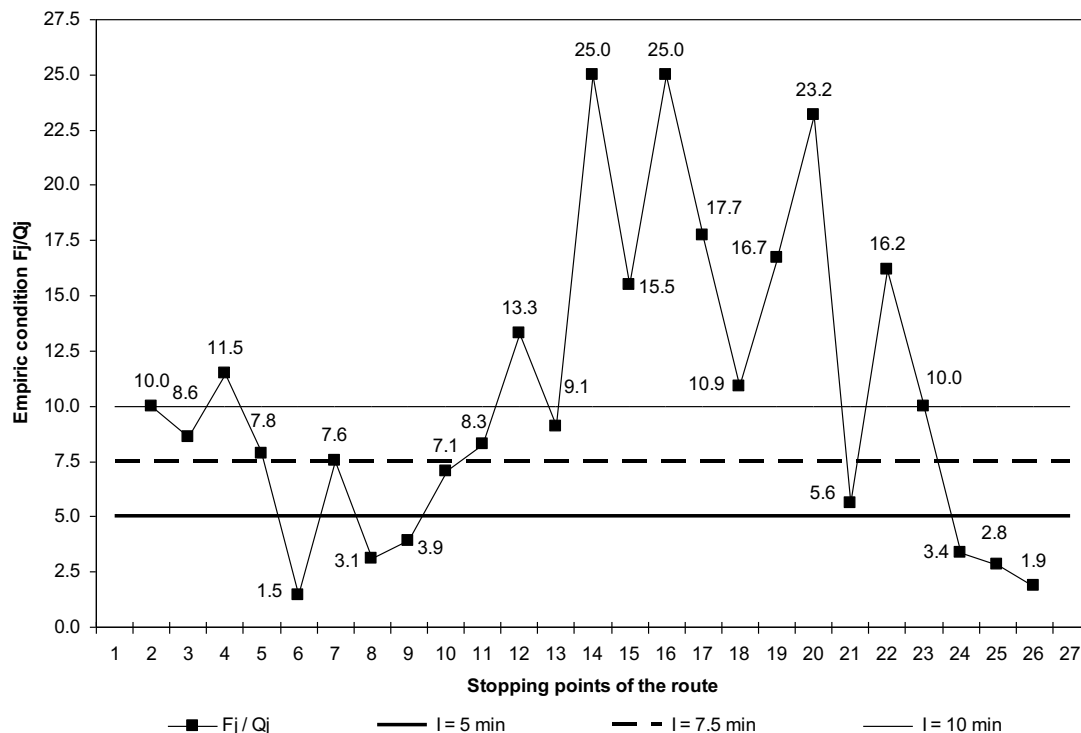


Fig. 3. Substantiation of the expediency of stopping points availability within a high-speed route

Relying upon the analysis of the data, containing in Fig. 3, the authors propose to make following conclusions:

1. such intermediate stops as 6, 8, 9, 21, 24, 25, and 26 should be involved categorically to the high-speed route;
2. possible adding of such intermediate stops as 5, 7, and 10 since $F_j/Q_j \in I...1.5I$ is for them; and
3. potential adding of such intermediate stops as 2, 3, 11, 13, and 23 since $F_j/Q_j \in 1.5I...2I$ is for them.

Thus, the three variants of a logic vector (12) of stopping points to be a part of the high-speed route have been formed:

- required: 1→6→8→9→21→24→25→26→27;
- possible: 1→5→6→7→8→9→10→21→24→25→26→27;
- potential: 1→2→3→5→6→7→8→9→10→11→13→21→23→24→25→26→27.

Names of the route variations are of purely relative nature proceeding from mathematical formulation of empiric condition (13). The stage of the combined transportation types implementation cannot determine definitely the best variant among the proposed ones relying upon the formulated efficiency criteria (8-9). That will become known only after the modeling results are processed.

3.5. Calculation of performance data of a transportation process within a route in terms of the specified parameters of a high-speed conveyance implementation

The following are output data to determine performance data of a transportation process in terms of the specified parameters of a high-speed conveyance implementation:

1. Road transport vehicles capacity q , passengers;
2. Number of buses, operating in a customary A^{CUST} mode and high-speed A^{HS} one;
3. Terminal delay of buses t_t , minutes;
4. Run between any stopping points within $l_{i,i+1}$ route, kilometers;
5. Matrix for inter-stop communications for calculation period K_{ij} , passengers; and
6. Matrix of bus traffic rate time within the route runs when it operates in a customary mode.

Works [6, 8-9, 11, 14, 24-30] describe rather completely basic dependences to determine core technical and economic performance (TEP) of a transportation process (i.e. transportation capacities, unproductive transportations, coefficients to use the capacities, total expenditures connected with passenger time consumed for transportation etc.); thus, the paper will not cite them.

Matrix elements of inter-stop communications are the key output data to determine the abovementioned TEP. Their constant rearrangement (with the sufficient accuracy) among transportation types depending upon the number of stopping points in the context of a high-speed route, run lengths, and the number of buses, operating in the corresponding modes is the major problem. To implement a procedure for such a rearrangement, authors of [1] propose a technique based on logical analysis of two matrices: a matrix of inter-stop communications, and a matrix of rate time for buses to travel a distance between the stopping points.

To identify the number of passengers who can use a customary transportation type only, it is required to separate from inter-stop communication matrix K_{ij} those passenger communications, which can use customary transportation type according to $(i \rightarrow j)$ directions in terms of the specified Z_i . Signify a set of such directions as A . It involves the runs where at least one of terminal points (ij) is not from the set of stopping points of a high-speed route, i.e., $\lambda_i \neq 1$ or $\lambda_j \neq 1$ condition is met. Otherwise, passengers either will not be able to get into the buses as they have not their stop within i^{th} point or they will not get to their destination points as they go by j^{th} point. The passengers, belonging to set A , form a matrix whose elements can be determined on the dependence:

$$q_{ij}^{CUST}(A) = \begin{cases} K_{ij}, & \text{if } \lambda_i \neq 1 \text{ or } \lambda_j \neq 1 \\ 0 & \end{cases} \quad (14)$$

In the context of other directions $(i \rightarrow j)$, $(\lambda_i = 1 \text{ and } \lambda_j = 1)$ condition is met for stopping points where passengers can use both customary transportation type and high-speed one, signifying a set of such directions as B . The passengers, belonging to B set, form a matrix whose elements are identified according to the dependence:

$$q_{ij}^{CUST \text{ or } HS}(B) = \begin{cases} K_{ij}, & \text{if } \lambda_i = 1 \text{ and } \lambda_j = 1 \\ 0 & \end{cases} \quad (15)$$

While selecting conveyance type, passengers are motivated by an idea to minimize travel time. Relying upon the idea, volumes of transportation of passenger, using certain conveyance type, can be determined according to the rules:

- if $T_{ij}^{HS} < T_{ij}^{CUST}$ condition (specify a set of such directions as C) is met for $(i \rightarrow j)$ directions then the passenger, moving in the direction, uses high-speed type only;
- if $T_{ij}^{HS} > T_{ij}^{CUST}$ condition (specify a set of such directions as D) is met for $(i \rightarrow j)$ directions then a passenger may use any conveyance type. Almost certainly, the passenger will take any bus which is the first to arrive at the stopping points.

The passengers, belonging to a set C , form $q_{ij}^{HS}(C)$ matrix whose components are identified according to the dependence:

$$q_{ij}^{HS}(C) = \begin{cases} q_{ij}(B), & \text{if } B_{ij} = C \\ 0 & \end{cases} \quad (16)$$

For the D set passengers, high-speed conveyance is out of priority as $T_{ij}^{HS} > T_{ij}^{CUST}$. That is why, a passenger will take any bus which is the first to arrive at the stopping point (conveyance type is not important). Hence, the number of passengers, conveyed by either high-speed transportation type of customary one, is directly proportional to their travel frequency or to the number of trips (ψ^{HS} , ψ^{CUST}). Thus, rearrangement of the set D passengers among high-speed conveyance $q_{ij}^{HS}(D)$ and customary one $q_{ij}^{CUST}(D)$ will be performed according to the dependences:

$$q_{ij}^{HSB}(D) = \begin{cases} q_{ij}(B) \cdot \frac{\psi^{HSB}}{\psi^{HSB} + \psi^{3B}}, & \text{if } B_{ij} = D \\ 0 & \end{cases} \quad (17)$$

$$q_{ij}^{3B}(D) = \begin{cases} q_{ij}(B) \cdot \frac{\psi^{3B}}{\psi^{HSB} + \psi^{3B}}, & \text{if } B_{ij} = D \\ 0 & \end{cases} \quad (18)$$

Consequently, the number of the conveyed passengers, is arranged among the conveyance types as follows: $Q^{HS}(C+D)$ and $Q^{CUST}(A+D)$.

3.6. Transportation process modeling to determine rational parameters of the combined (i.e. high-speed) conveyance type implementation

The idea, concerning determination of rational parameters of the combined transportation type, is like this. While varying a combination of stopping points of high-speed conveyance (Z_i) as well as the number of buses performing high-speed trips (A^{HS}) and customary ones (A^{CUST}), it is possible to obtain a set of values of $F(Z_i, A^{CUST}, A^{HS})$ functional. As it has been considered in point 3.2, either unproductive transportation value W_N (8) or total passenger time consumed including time for transportation and waiting time $\sum T$ (9) may serve as F functional. Hence, a set of $\{F\}$ values should be used to select the best variant from the viewpoint of the selected efficiency criterion and constraint system as well as to determine (Z_i, A^{CUST}, A^{HS}) values in terms of which the functional achieve its minimum ($\min F$).

In terms of the selected combination (Z_i) and stipulated number of buses involved in high-speed conveyance ($A^{HS} = const$), the increase in the quantity of the buses involved in customary conveyance reduces waiting time as well as total passenger time for transportation. On the contrary, the increased number of buses involved in a customary trips increases volume of the specified transportation $P_{specified}$ resulting in the increased unproductive transportation W_N in terms of a constant quantity of the used passenger-kilometers P_{actual} .

The modeling is required for several data groups; for each of them $A^{CUST} = const \in A-1$ ($A^{CUST} = A$ variant corresponds to a customary transportation mode within a route), and $A^{HS} \in [1; A - A^{CUST}]$. For instance, in terms of the urban route, considered as an example (Fig. 4) 15 buses operate; thus, it is necessary to calculate 105 variants to implement the combined conveyance for different ratios

(A^{CUST} , A^{HS}) for each combination of stopping points in the context of high-speed conveyance (Z_i). Taking into consideration data in Fig. 4, total number of F functional (Z_i , A^{CUST} , and A^{HS}) is 315 values. The core technical and economic performance of transportation process for the variants was calculated with the help of *Microsoft Excel* environment appendix, developed by the authors.

Analysis of the obtained calculations determines potential area of tolerance extent of unproductive transportation W_N . On top, the area is limited by a level of unproductive transportation determining a variant when customary conveyance is the only applicable type (in terms of the considered example, all the buses operate in a customary mode $W_N = 313.2$ pas·km). It is obvious that from the viewpoint of the selected efficiency criterion $W_N \rightarrow \min$, excess of the boundary is not expedient while implementing high-speed transportation within the route.

Below, the area is limited by $W_N \geq 0$ level, as under negative W_N value, the specified transportation is less than the required one. In the context of the variants, implementation of high-speed transportation types will definitely result in the worsening conveyance service where average values of capacity use coefficient will exceed tolerable level significantly ($\bar{\gamma} \gg 1$). To reduce the number of variants, involving further analysis for each $A^{CUST} = const$ list, the only one, providing $W_N \rightarrow \min$, has been selected (Table 3).

Table 3

The best variants to implement high-speed transportation if ($W_N \rightarrow \min$, $W_N \geq 0$) (fragment)

Z_i	The number of buses		W_N , pas·km	Capacity use coefficient		$\sum T$, hours
	A^{CUST}	A^{HS}		γ^{CUST}	γ^{HS}	
1	1	10	57	7.52	0.48	226.8
1	2	10	231	3.76	0.48	149.2
1	3	9	158	2.51	0.54	124.3
1	4	8	109	1.88	0.60	112.2
1	5	7	43	1.50	0.70	105.7
1	6	6	9	1.25	0.80	101.9
1	7	6	182	1.07	0.80	98.3
1	8	5	113	0.95	0.96	97.8
1	9	4	66	0.85	1.18	98.0
1	10	3	23	0.79	1.52	101.0
1	11	3	172	0.74	1.48	99.6
1	12	2	124	1.06	0.47	101.0

Analysis of the data, represented in Table 3 confirms that reduction in the unproductive transportation may be achieved in terms of different variants of high-speed conveyance implementation including those, unacceptable from the viewpoint of transportation service. In fact, it is almost impossible to implement transportation within a route where bus fullness is $\gamma > 2$, and the highest economic and social effect is observed when capacity use coefficient will work for 1 in the context of the both transportation types. Moreover, such quality index of conveyance service as total passenger time consumed for transportation should also be involved.

Relying upon the aforesaid, it becomes necessary to evaluate the obtained results integrally basing on the generalized efficiency index which would involve each basic factors of the transportation process. The authors propose to apply the criterion to evaluate i^{th} variant to implement the combined (i.e. high-speed) conveyance mode:

$$K^i_{f(Z, A^{CUST}, A^{HS})} = \begin{cases} 0, & \text{if } K^i(\gamma) = 0 \\ K^i(W_N) + K^i(\gamma) + K^i(\sum T) & \end{cases} \rightarrow \min, \tag{19}$$

where $K^i(W_N)$ is the factor involving the reduced unproductive transportation; $K^i(\gamma)$ is the factor involving optimum bus fullness; and $K^i(\sum T)$ is the factor involving the reduced time consumed including time for transportation and waiting time.

It is proposed to calculate criterion (19) components according to the dependences:

$$K^i(W_N) = \begin{cases} 1.00, & \text{if } W_N^i = W_N^{\min} \\ 2.00, & \text{if } W_N^i = W_N^{\max} \\ \left(1 + \frac{W_N^i - W_N^{\min}}{W_N^{\max} - W_N^{\min}}\right) & \end{cases} \quad (20)$$

$$K^i(\gamma) = \begin{cases} 0, & \text{if } K^i(\gamma_{CUST}^i) = 0 \text{ or } K^i(\gamma_{HS}^i) = 0 \\ K(\gamma_{CUST}^i) + K(\gamma_{HS}^i) & \end{cases} \quad (21)$$

$$K^i(\gamma_{CUST}^i) = \begin{cases} 0, & \text{if } \gamma_{CUST}^i > 2 \\ \gamma_{CUST}^i \cdot 100\%, & \text{if } \gamma_{CUST}^i > 1 \\ (1 + [1 - \gamma_{CUST}^i]) \cdot 100\%, & \text{if } \gamma_{CUST}^i < 1 \end{cases} \quad (22)$$

$$K^i(\gamma_{HS}^i) = \begin{cases} 0, & \text{if } \gamma_{HS}^i > 2 \\ \gamma_{HS}^i, & \text{if } \gamma_{HS}^i > 1 \\ (1 + [1 - \gamma_{HS}^i]), & \text{if } \gamma_{HS}^i < 1 \end{cases} \quad (23)$$

$$K^i(\sum T) = \begin{cases} 1.00, & \text{if } \sum T^i = \sum T^{\min} \\ 2.00, & \text{if } \sum T^i = \sum T^{\max} \\ \left(1 + \frac{\sum T^i - \sum T^{\min}}{\sum T^{\max} - \sum T^{\min}}\right) & \end{cases} \quad (24)$$

Taking into consideration the proposed structure of the complex efficiency index of the combined transportation implementation (19-24), it is possible to say that its value is 4.00 for perfect conditions, and 8.00 for the most unfavourable ones. Fig. 4 demonstrates the performed calculation results for the considered route according to (19-24); the best variants are red and green.

Hence, the most rational indices of transportation process are possible if the route involves 6 buses operating in high-speed mode, and 6 buses, operating in customary mode ($A^{CUST} = 6$, and $A^{HS} = 6$), and stopping points of the high-speed route belong to $Z_1(1 \rightarrow 6 \rightarrow 8 \rightarrow 9 \rightarrow 21 \rightarrow 24 \rightarrow 25 \rightarrow 26 \rightarrow 27)$ set.

4. CONCLUSIONS

The paper considers the problems concerning the improvement of passenger transportation process at the expense of the combined operating mode implementation. Implementation of the measure helps minimize unproductive transportation operations of road transport vehicles with no passenger service deterioration; moreover, it also results in significant reduction of expenses for combustible and lubrication materials as well as emission reduction.

The examples and the explained mechanism to improve the efficiency of bus operation as well as service quality increase while the measure implementations have been adduced. Critical analysis of the available techniques to select bus operation mode has been mentioned; their application area, advantages, and disadvantages have been listed. Efficiency criteria to implement the mixed conveyance forms have been formulated. An extensive approach to determine stopping points, involved in a high-speed route, has been proposed.

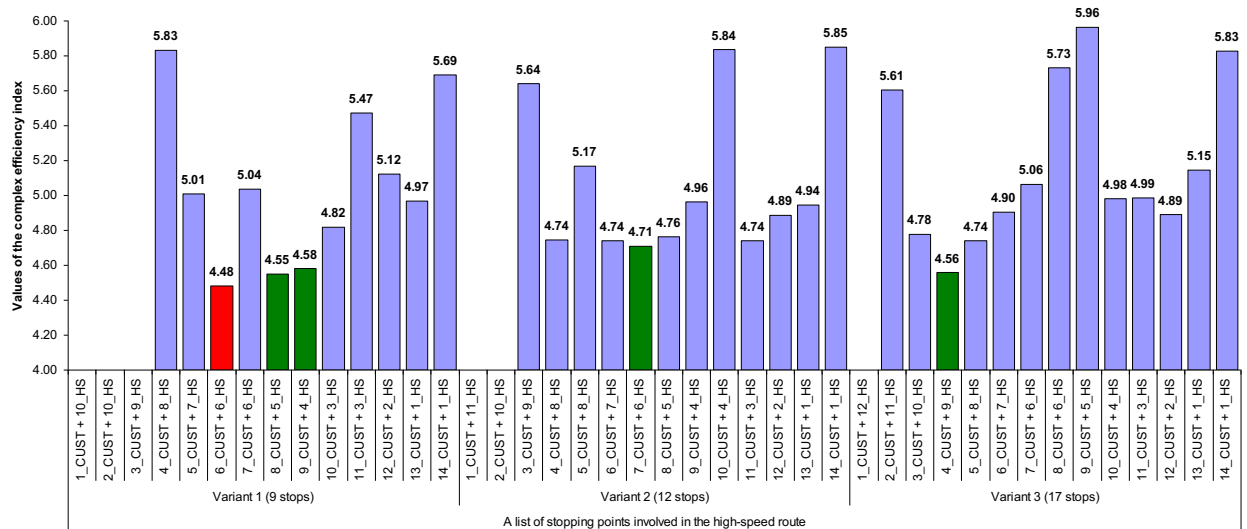


Fig. 4. Values of the complex efficiency index for the variants to implement the combined (i.e. high-speed) conveyance mode

Economic and mathematical model has been developed; the model makes it possible to find out and determine the expediency as well as rational parameters to implement combined high-speed conveyance types within certain urban route. To implement the procedure of passenger redistribution among the bus services, a technique, basing upon logic analysis of two matrices (i.e. interstop correspondence matrix, and a matrix of standard time for a bus to pass distance between two stopping points) has been proposed. Complex efficiency parameter has been proposed to analyze a set of variants concerning the combined conveyance mode implementation involving basic economic, technological, and social indices of passenger transportation.

The paper represents modeling results for an urban route where the combined transportation will help to:

- reduce duration of trip of buses, involved in high-speed transportation, from 38 down to 29 minutes (i.e. by 23%);
- increase operational speed of buses, involved in the high-speed mode from 19.2 up to 25,4 km/hour (i.e. by 25%);
- release 3 units of road transport vehicles;
- reduce transportation passenger loss from 86.3 down to 65.4 hours; and
- reduce unproductive transportation value from 313.2 down to 9 pas·km.

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