MODELING THE CAPACITY OF COLLECTION POINTS FOR ELECTRONIC HOUSEHOLD WASTE IN CITIES

Abstract. This paper presents guidelines for modeling the capacity of electronic household waste collection points. These points are used as infrastructure elements with a multi-stage logistic support scheme for the electronic waste disposal process. This paper includes theoretical and methodological information on the procedure for placing points of waste collection in cities using the processes of determining the parameters of waste accumulation, calculating the design capacity of warehouses at these points, and developing routes for the transportation of waste to the places of their disposal. We represent the dependence of the logistic support costs, including the costs of maintaining waste collection points, and waste disposal to utilization facilities, on the duration of the waste accumulation period. A mathematical model for optimizing the logistic support costs is developed, which takes into account the most important parameters of the waste disposal system, namely, the topology of the collection points, the intensity of waste accumulation, the configuration of the routes, and the vehicle carrying capacity. Using the example of the Vietnamese capital, the city of Hanoi, the required number of waste collection points is calculated, the volume of waste accumulation at each point is determined, the optimal period of waste accumulation, in which the total costs for logistic support for the disposal process will be minimal, is determined. Recommendations on the organization of waste transportation, depending on the actual level of filling the capacity of collection and accumulation points, are given.

Keywords: E-waste, electronic household waste, transport, waste collection points, recycling waste, waste recycling points, logistic support, modeling


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отходов. Разработана математическая модель по оптимизации затрат на логистическую поддержку, принимающая во внимание наиболее важные параметры системы вывоза и захоронения мусора, такие как топология пунктов сбора, интенсивность накопления отходов, конфигурация маршрутов, грузовместимость транспорта. На примере столицы Вьетнама – г. Ханой – подсчитано необходимое количество пунктов сбора мусора и рассмотрен объем накопления отходов на каждом из них, установлен оптимальный период накопления мусора, при котором совокупные расходы на логистическую поддержку вывоза и захоронения бытовых отходов минимальны. Выработаны рекомендации по организации транспортировки бытового мусора в зависимости от непосредственного уровня наполненности емкостей пунктов сбора коммунально-бытовых отходов.

**Ключевые слова:** логистическое обеспечение, моделирование, электронные отходы, электронные бытовые отходы, транспорт, пункты приема отходов, утилизация отходов, пункты утилизации отходов


**Introduction.** In recent years, the improvement of the efficiency of the waste management process has been of great interest to the state and public structures. This problem is the most topical in large cities with high population density and concentration of industrial production facilities. Moreover, in modern conditions, the highest growth rates of electronic equipment waste (referred as electronic waste) in these territories are noted [1–3]. Electronic waste includes various objects with electrical or electronic components, nodes and consumables (computer equipment, monitors, motherboards and chips, peripherals, lamps, including mercury and luminescent ones, large home appliances, electronic and optical equipment and tools, etc.) that lost their consumer properties due to the failure, breakage, resource exhaustion, expiry, etc. [4–6].

All types of electronic waste contain hazardous substances, which, in non-compliance with the rules of disposal, can cause significant harm to the health of people and the environment. Therefore, it is necessary to ensure their complete disposal. However, nowadays, a significant part of electronic household waste (hereinafter referred to as EHW, E-Waste), generated by the population, is not disposed of properly and thrown away along with garbage – municipal solid waste (hereinafter – MSW). Such behavior is caused by the lack of EHW collection points (hereinafter – WCP) in cities. At the same time, the creation of WCP is associated with significant expenditures on logistic support for their activities – the maintenance and transport support of such points. Therefore, it is necessary to make economically reasonable decisions on the capacity of WCP, which provides minimal logistic support costs [7]. At the same time, the analysis of scientific works has shown that currently these issues are not studied enough. Therefore, it seems that the task of developing a method for substantiating the WCP capacity by the criterion of minimum logistic support costs is relevant.

**Materials and Methods.** To optimize the cost of collection, accumulation, and transportation of EHW, the methods developed on the basis of the theoretical and methodological provisions of logistics are used [8–11]. Logistic support for the EHW disposal process is to ensure the timely and cost-effective movement of e-waste on all links of the return logistics chain. To dispose of EHW, a two-stage logistic support scheme is used, which contains the following operations:

- collection and accumulation of EHW at WCP;
- transportation of EHW to EHW recycling points (hereinafter – WRP).

A single-stage logistic support scheme in which EHW moves from the population directly to the WRP, bypassing the WCP, is rarely applied in practice [12–15].

A typical WCP is an infrastructure facility in which there are rooms for staff placement, special equipment for collection and temporary storage of e-waste, tools for processing and preparing waste to transportation. Operations for collection and accumulation of EHW for subsequent transportation to the WRP are carried out at the WCP [16]. Collection means obtaining electronic waste from the population. The accumulation operation is the storage of waste from the population during the prescribed period of time for the formation of enlarged cargo lots in order to increase the efficiency of transportation. Transportation means the process of transporting the accumulated waste from the WCP to the WRP, which includes the operations of loading and unloading waste, vehicle movement along the route – empty mileage from the WRP to the first WCP, loaded trip through all WCPs included in the route and back to the WRP.
Each \( i \)-th WCP is created to serve the population within the boundaries of a specific section \( d_{pi} \) \((i = 1, \ldots, D_p)\) based on the rule “One section – one WCP” \((D_p = N_p)\). The total number of sections \( D_p \) and, accordingly, the total \( N_p \) amount of WCPs placed within the borders of the section are set taking into account the local characteristics of the specific settlement, the social composition of the population, the configuration of the transport network, and other factors. At the same time, the parameters of the sections and the location of WCPs must provide the population with the convenient conditions for moving EHW to the WCP [17, 18].

This study was performed using the example of the Vietnamese capital, the city of Hanoi, in which only 5 official WCPs were created in three parts of the city: 2 points in the Cau Giay district, 2 – in the Ba Dinh district, 1 – in the Hoan Kiern district. According to the Report on the program Vietnam Recycles – 2019 “E-waste in Ha Noi Area”, there are no WCPs in one of the largest urban areas – the Hoang Mai district. In this district, \( N_R = 423 \) thousand people live on the territory with a total area of \( F_R = 41 \text{ km}^2 \); the population density thus being \( P_R = 10.3 \text{ thousand people} / \text{ km}^2 \). Due to the lack of WCPs, the total volume of EHW officially utilized in the Hoang Mai district is less than 1 %, and the main part of EHW is disposed of with MSW.

The survey of residents of the Hoang Mai district has shown that the long distance of WCPs from accommodation places reduces the motivation to comply with the EHW disposal rules. Based on the results of the survey of residents of the district, the permissible distance of the WCP from the people accommodation is determined: \( L_p = 0.9 \text{ km} \). This indicator sets the borders of the \( d_{pi} \) sections to place WCPs. Each section is a square cell with a width \( L_B \) and a height \( L_H \) equal to the double value of \( L_p \). The area of each site \( F_p \) amounted to:

\[
F_p = L_B \cdot L_H = (2 \cdot L_p)^2 = 4 \cdot 0.81 = 3.24, \text{ km}^2.
\] (1)

Taking into account this parameter, thirteen sections are defined \((N_p = 13 \text{ units})\) to place WCPs in the Hoang Mai district. The actual location of individual WCPs was determined taking into account the architectural and planning features of the terrain and the availability of the engineering infrastructure.

The potential average daily volume \((Q_D, \text{ tons per day})\) of the EHW formation within the boundaries \( d_{pi} \) of the section is determined taking into account the average daily intensity of the electronic waste generation \( W_D \) in the city, the area of the section \( F_p \), and the population density in the area \( P_R \):

\[
Q_D = W_D \cdot F_p \cdot P_R = 7.4 \cdot 10^{-3} \cdot 3.24 \cdot 10.32 = 0.25 \text{ t/d}.
\] (2)

The following table shows the indicators of population density and the average daily intensity of the generation of electronic waste \((W_D = 7.4 \cdot 10^{-3} \text{ kg/people-day})\) for the Hoang Mai district. Values are set based on the official statistical data.

**Characteristics and intensity of EHW generation in Hanoi districts**

<table>
<thead>
<tr>
<th>Names of the city districts</th>
<th>Number of residents of the district ( N_p ) ( \times 10^3 ) thousand people</th>
<th>Area of the district ( F_p, \text{ km}^2 )</th>
<th>Population density in the district ( P_p, \text{ thousand people} / \text{ km}^2 )</th>
<th>The average EHW generation intensity in the district ( W_{ee}, 10^{-3} \text{ kg/people-day} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanoi, in total, including:</td>
<td>8053</td>
<td>3358.6</td>
<td>2.40</td>
<td>7.40</td>
</tr>
<tr>
<td>Hoan Kiem</td>
<td>147.3</td>
<td>5.29</td>
<td>27.84</td>
<td>7.26</td>
</tr>
<tr>
<td>Dong Da</td>
<td>430.05</td>
<td>9.95</td>
<td>43.22</td>
<td>6.99</td>
</tr>
<tr>
<td>Ba Dinh</td>
<td>247.1</td>
<td>9.21</td>
<td>26.83</td>
<td>7.12</td>
</tr>
<tr>
<td>Hai Ba Trung</td>
<td>321.5</td>
<td>9.62</td>
<td>33.42</td>
<td>6.58</td>
</tr>
<tr>
<td>Hoang Mai</td>
<td>423</td>
<td>41</td>
<td>10.32</td>
<td>7.40</td>
</tr>
<tr>
<td>Thanh Xuan</td>
<td>292.8</td>
<td>9.11</td>
<td>32.14</td>
<td>6.90</td>
</tr>
<tr>
<td>Long Bien</td>
<td>322.5</td>
<td>61</td>
<td>5.29</td>
<td>7.15</td>
</tr>
<tr>
<td>Nam Tu Liem</td>
<td>269.07</td>
<td>32.17</td>
<td>8.36</td>
<td>6.44</td>
</tr>
<tr>
<td>Bac Tu Liem</td>
<td>340.6</td>
<td>45.24</td>
<td>7.53</td>
<td>6.77</td>
</tr>
<tr>
<td>Tay Ho</td>
<td>171.2</td>
<td>24</td>
<td>7.13</td>
<td>7.21</td>
</tr>
<tr>
<td>Cau Giay</td>
<td>292.5</td>
<td>12.44</td>
<td>23.51</td>
<td>5.75</td>
</tr>
<tr>
<td>Ha Dong</td>
<td>402</td>
<td>49.64</td>
<td>8.10</td>
<td>6.42</td>
</tr>
</tbody>
</table>
For the disposal of e-waste, the transportation is organized from all WCPs, at least one ring route with a sequential visit of WCPs. The total number of routes $N_M$ is established depending on the total e-waste generation volume at all points $N_P$ of the serviced area and the carrying capacity of the vehicle used for e-waste transportation:

$$N_M = \sum_{i=1}^{N_P} \frac{Q_{Wi}}{q} = \frac{T_W \cdot Q_D \cdot N_P}{q}, \text{ un.,}$$  

(3)

where $q$ is the Load capacity of the specialized rolling stock, tons; $Q_{Wi}$ is the volume of the accumulated e-waste in the $i$-th WCP.

The accumulation period $T_W$ is used to assign the e-waste transportation intervals $Y_{Mj}$ for each $j$-th route ($j = 1, \ldots, N_M$):

$$Y_{Mj} = T_W, \text{ days.}$$  

(4)

The number of points $N_{Nj}$ serviced by a separate $j$-th route is established taking into account the carrying capacity $q$ of the specialized rolling stock used on the line, and the amount $Q_W$ for the period $T_W$:

$$N_{Nj} = \frac{q}{Q_D \cdot T_W}, \text{ un.}$$  

(5)

The total number $N_{Tj}$ of cycles of the e-waste disposal for each route during a planning period $T_Y$ (year) will be:

$$N_{Tj} = \frac{T_Y}{T_W}, \text{ un.}$$  

(6)

The mileage of the rolling stock $L_{Mj}$ for each $j$-th route is calculated as the sum of three types of mileages:

$$L_{Mj} = L_{BAj} + L_{Wj} + L_{ABj}, \text{ km,}$$  

(7)
where \( L_{BAj} \) and \( L_{ABj} \) are initial and final mileages of the rolling stock following from the WRP to the first WCP on the route for loading and from the last WCP to the WRP for unloading, respectively, km; \( L_{Wj} \) is the mileage of the rolling stock between all WCPs of the \( j \)-th route, km.

As part of this study, the initial \( L_{BAj} \) and the final \( L_{ABj} \) mileages for all routes can be taken equal and amount to half of the longest length \( L_D \) inside the boundaries of the district (for example, diagonally or diameter):

\[
L_{BAj} = L_{ABj} = \frac{L_D}{2}, \text{ km.} \quad (8)
\]

For a uniformly distributed network of sections through the district territory, the length \( L_{Wj} \) between any neighboring WCPs is also taken equal to \( L_{FL} \) and calculated by the formula:

\[
L_{FL} = \sqrt{F_p} = 2 \cdot L_P, \text{ km.} \quad (9)
\]

Then the mileage \( L_{Wj} \) of the rolling stock between the adjacent WCP along the \( j \)-th route will be:

\[
L_{Wj} = L_{FL} \cdot (N_{Nj} - 1) = 2 \cdot L_P \cdot \left( \frac{q}{Q_D \cdot T_W} - 1 \right), \text{ km.} \quad (10)
\]

The general mileage \( L_{Mj} \) of the rolling stock on the route as a whole will be:

\[
L_{Mj} = \frac{L_D}{2} + 2 \cdot L_P \left( \frac{q}{Q_D \cdot T_W} - 1 \right) + \frac{L_D}{2} = L_D + 2 \cdot L_P \cdot q \cdot Q_D \cdot T_W - 2 \cdot L_P, \text{ km.} \quad (11)
\]

It is important to note that when the amount of accumulation \( Q_W \) in each WCP for the period \( T_W \) is larger than the carrying capacity \( q \) of the rolling stock, then the pendulum routes should be generated, one route to each WCP. On the pendulum routes, there are no mileages \( L_{Wj} \) between adjacent WCPs, and the total mileage along the route \( L_{Mj} \) is the length from the WRP to some WCP and back:

\[
L_{Mj} = L_{BA} + L_{AB} = L_D, \text{ km.} \quad (12)
\]

**Results.** The design capacity \( Q_{Bi} \) of the warehouse of each \( i \)-th WCP should be sufficient to store the EHW in the amount of \( Q_{Wi} \) accumulated during the period \( T_{Wi} \). Since the e-waste generation volumes \( Q_D \) and the accumulation periods \( T_W \) for all WCPs in the served district are set as the same, the design capacity \( Q_{Bi} \) of warehouses in all WCPs will also be the same and equal:

\[
Q_{Bi} = Q_{Wi} = Q_D \cdot T_W, \text{ tons.} \quad (13)
\]

With the well-known capacity of the \( i \)-th point \( Q_{Bi} \) within the district area, it is possible to determine the capacity \( Q_{RB} \) of the entire WCP network:

\[
Q_{RB} = \sum_{i=1}^{N_P} Q_{Bi} = T_W \cdot Q_D \cdot N_P, \text{ tons.} \quad (14)
\]

The minimum warehouse capacity \( Q_{Bmin} \) corresponds to the average daily volume of e-waste generation \( Q_D^* \):

\[
Q_{Bmin} = Q_D^*, \text{ at } T_W = 1 \text{ day.} \quad (15)
\]

With \( Q_{Bmin} \), costs \( S_{CB} \) for the maintenance of all WCPs (rental, operating costs, etc.) will be minimal. However, in this case, it is necessary to ensure the daily removal of small e-waste batches, which will lead to high transport costs \( S_{CT} \). Increasing the accumulation period \( T_W > 1 \) will require an increase in the capacity of WCP warehouses, which will lead to an increase in the cost \( S_{CB} \) for the maintenance of the infrastructure object. With \( T_W > 1 \), the e-waste transportation intervals will also increase, and the cost of transporting \( S_{CT} \) as a result, will decrease. The dependences of the costs \( S_{CP} \) and \( S_{CT} \) on \( T_W \) make it possible to formulate a statement regarding the capacity \( Q_{B} \) of the WCP warehouse. Firstly, the capacity \( Q_{B} \) should be sufficient to accommodate the entire volume \( Q_{W} \) of the accumulated EHW for the peri-
od $T_w$, and therefore should be calculated based on the established duration $T_w$. Secondly, when choosing a design value of capacity $Q_B$, it is necessary to take into account the cost criterion – the total costs $S_{BT}$ for logistic support for the EHW disposal process (costs calculated in Vietnamese dongs, VND):

$$S_{BT} = S_{CB} + S_{CT}, \text{ VND.} \quad (16)$$

Since the maintenance costs of all infrastructure objects $S_{CB}$ is in direct dependency on their capacity ($Q_B$), and the cost of removal $S_{CT}$ is reduced as this capacity increases, such a value of $Q_B$ can be found, in which an increase in $S_{CB}$ will be overlapped with a decrease in $S_{CT}$, the total $S_{BT}$ costs will be minimal.

Costs $S_{CB}$ for the maintenance of the WCP network depend on the overall capacity of points and are calculated by the formula:

$$S_{CB} = Q_B \cdot U_B \cdot T_Y = T_W \cdot Q_D \cdot N_P \cdot U_B \cdot T_Y, \text{ VND,} \quad (17)$$

where $U_B$ is the rate of the cost of maintaining a single tank at the WCP, i.e. 1 ton per day, VND/t·d.

Costs $S_{CT}$ on the removal of e-waste from the WCP to the WRP are calculated by the formula:

$$S_{CT} = Q_{CT} \cdot U_T, \text{ VND,} \quad (18)$$

where $Q_{CT}$ is the volume of the transport work performed when removing a planned $Q_{CT}$ number of EHW, t·km/year; $U_T$ is the Cost rate per unit of the completed transport work, i.e., 1 t·km, VND/t·km.

The calculation of transport costs is based on the following assumptions: all sections within the boundaries of the district have the same area $F_P$, the number $N_R$ and the density $P_R$ of residents; all WCPs have the same capacity $Q_B$; there are transport communications between all WCPs; routes are built along the shortest distance through the sequential transport stops at the adjacent WCPs. Then the value of costs $Q_{CT}$ planned to export from all WCP during the year is determined by the formula:

$$Q_{CT} = \sum_{j=1}^{N_M} (N_{Tj} \cdot Q_{Mj} \cdot L_{Mj}), \text{ t·km,} \quad (19)$$

where $Q_{Mj}$ is the volume of EHW removed from all WCPs included in each $j$-th route, tons.

The amount $Q_{Mj}$ of the transported e-waste for each route is established taking into account the carrying capacity $q$ of the specialized rolling stock used on the line. With full use of the carrying capacity of the rolling stock we have $Q_{Mj} = q$.

Taking into account the above-mentioned formulas for the calculation of variables, the total volume of the transport work $Q_{CT}$ will be:

$$Q_{CT} = \frac{T_Y \cdot T_W \cdot Q_D \cdot N_P}{q} \cdot \left( \frac{L_D + 2 \cdot L_P \cdot q}{Q_D \cdot T_W} - 2 \cdot L_P \right) =$$

$$= T_Y \cdot N_P \cdot Q_D \cdot L_D + T_Y \cdot N_P \cdot Q_D \cdot \frac{2 \cdot L_P \cdot q}{Q_D \cdot T_W} - T_Y \cdot N_P \cdot Q_D \cdot 2 \cdot L_P =$$

$$= \frac{T_Y \cdot N_P \cdot 2 \cdot L_P \cdot q}{T_W} + T_Y \cdot N_P \cdot Q_D \cdot (L_D - 2 \cdot L_P), \text{ t·km.} \quad (20)$$

Based on the obtained value of $Q_{CT}$, let us define the annual costs $S_{CT}$ of the e-waste transportation:

$$S_{CT} = \frac{T_Y \cdot N_P \cdot 2 \cdot L_P \cdot q}{T_W} + T_Y \cdot N_P \cdot Q_D \cdot U_T \cdot (L_D - 2 \cdot L_P), \text{ VND.} \quad (21)$$

Now the total cost of logistic support for the disposal process $S_{BT}$ can be determined:

$$S_{BT} = S_{CB} + S_{CT} = T_W \cdot Q_D \cdot N_P \cdot U_B \cdot T_Y + \frac{T_Y \cdot N_P \cdot 2 \cdot L_P \cdot q}{T_W} \cdot U_T +$$

$$+ T_Y \cdot N_P \cdot Q_D \cdot U_T \cdot (L_D - 2 \cdot L_P), \text{ VND.} \quad (22)$$
Graphs of changes in the costs of logistic support ($S_{CB}$, $S_{CT}$, $S_{BT}$, VND) for different values of the accumulation period $T_W$ (days). Source: authors’ calculations

Analysis of expression (22) shows that all indicators, except $T_W$, are constant values. Therefore, it is possible to find such a value of $T_W^*$ for which the cost of logistic support $S_{BT}$ will be minimal:

$$S_{BT} \rightarrow \min.$$

Let us differentiate function $S_{BT}$ (22), equate the resulting expression to zero and find $T_W^*$ with which the minimum cumulative costs $S_{BT}$ for logistic support for the disposal process are ensured:

$$T_W^* = \frac{2 \cdot L_D \cdot q \cdot U_T}{U_B \cdot Q_D}, \text{ days.}$$

Using the source data in the Hoang Mai district, we define the optimal period of accumulation $T_W^*$. The following values were used for calculations: $T_Y = 365$ days; $L_D = 0.9$ km; $q = 5$ t; $U_T = 560$ VND/t·km; $N_p = 13$ units; $U_B = 790$ VND/t·d; $Q_D = 0.25$ t/d:

$$T_W^* = \frac{2 \cdot 0.9 \cdot 5 \cdot 560}{790 \cdot 0.25} = 5.05 \approx 5, \text{ days.}$$

Using formula (22), let us define the summary costs for logistic support $S_{BT}$ for the calculated value of $T_W = 5$ days, with $L_D = 8.1$ km: $S_{BT} = 13 \, 653 \, 738$ VND/year. At $T_W^* = 5.05$ days, the total costs will be $S_{BT} = 13 \, 653 \, 238$ VND/year, which is less than the calculated for $T_W = 5$ days by 499 VND. Thus, rounding caused a slight increase in costs – less than 0.01% of the optimal option. Table 2 shows the results of the calculation of the total costs of logistic support $S_{BT}$ for various values of the accumulation period $T_W$ (from 1 to 30 days).

Based on the obtained data, graphs (Figure) of changes in logistic support costs ($S_{CB}$, $S_{CT}$, $S_{BT}$) are built for various values of the accumulation period $T_W$.

**Discussion and conclusions.** The developed method of planning the WCP capacity is based on determining the optimal value of the period $T_W^*$ of e-waste accumulation. One should bear in mind that the process of EHW accumulation is caused by random factors that affect the performance of various types of electronic and electrical equipment. This means that with an average intensity $W_D$ of EHW generation during the period $T_W$, the volume $Q_W$ will accumulate at the $i$-th WCP. However, this process will be uneven, and it is possible that the volume of $Q_W$ will be accumulated before the end of the period $T_W$. Consequently, at $T_W > 1$, situations of a deficit in the WCP capacity may occur until the planned removal of e-waste in accordance with the interval $Y_{MP'}$. With a shortage of WCP capacity, the population will not be able to send e-waste for disposal, which is unacceptable. Therefore, when $T_W^* > 1$, it is advisable to or-
organize the removal of EHW according to the “actual level of filling the WCP capacity” on the days when the volume of accumulation $Q_{W}$ reaches the capacity of the point $Q_{B}$.

It should also be noted that when calculating transport costs, we used the values of indicators (in particular, the number of routes, the number of waste collection points in one route, etc.), which characterize not the factual but the potentially necessary volume of transport work for the disposal of EHW. Therefore, the values of some indicators (for example, in formulas (3), (5), (6), etc.) can take non-integer values. However, when organizing work of vehicles on routes, it is necessary to use indicators with integer values, which should be calculated on the basis of the factual data of speed vehicles along routes, the length of routes, the duration of the drivers’ working hours, etc.

References


Information about the authors

**Denis V. Kapski** – Dr. Sc. (Engineering), Dean of the Automotive and Tractor Faculty, Belarusian National Technical University (65, Nezavisimosti Ave., 220013, Minsk, Republic of Belarus). E-mail: d.kapsky@bntu.by

**Oleg N. Larin** – Dr. Sc. (Engineering), Professor at the Department of Logistic Transport Systems and Digital Technologies at the Institute of Management and Digital Technologies, Russian University of Transport (9, b9, Obrazcov Str., 127994, Moscow, Russian Federation). E-mail: larin_on@mail.ru

**Nguyen Thi Thu Huong** – Postgraduate Student, Plekhanov Russian University of Economics (36, Stremyanny Lane, 117997, Moscow, Russian Federation); Lecturer at the University of Transport Technology (Hanoi, Vietnam). E-mail: miss.huong@mail.ru

Информация об авторах

**Капский Денис Васильевич** – доктор технических наук, доцент, декан автотракторного факультета, Белорусский национальный технический университет (пр. Независимости, 65, 220013, Минск, Республика Беларусь). E-mail: d.kapsky@bntu.by

**Ларин Олег Николаевич** – доктор технических наук, профессор кафедры «Логистические транспортные системы и технологии», Российский университет транспорта (ул Образцова, 9, стр. 9, 127994, ГСП-4, Москва, Российская Федерация). E-mail: larin_on@mail.ru

**Нгуен Тхи Тху Хьонг** – аспирант, Российский экономический университет имени Г. В. Плеханова (Стремянный пер., 36, 117997, Москва, Российская Федерация); преподаватель Университета транспортных технологий (Ханой, Вьетнам). E-mail: miss.huong@mail.ru