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**Tetiana Tokmylenko,
Olena Chernyshova,
Vitalii Chyzhyk**

INVESTIGATION OF GREENHOUSE EMISSION INVENTORY FROM TRANSPORT SYSTEM FUNCTIONING IN LARGE AND MEDIUM CITIES

The object of the research of the article is transport system of a city. The paper reviews the necessity to assess the greenhouse emissions in the city and proposes the methods for greenhouse emissions inventory of the urban transport system. The proposed approach is aligned with guidelines for the development of Sustainable Energy and Climate Action Plan (SECAP) of Mayor Covenants of European Union (EU). The methodologies outlined in the paper allow to estimate annual greenhouse emissions from transport sector.

The SECAP defines transport sectors based on ownership and functioning as following: municipal transport fleet, public transport, and private and commercial transport. The paper proposes the methodology to estimate direct and indirect emissions in each of the described sector based on the information that is typicaly available to municipalities in Ukraine. The assessment is conducted on disaggregated level for different fuel types (diesel, petroleum, natural gas, biofuel, electricity, etc.) and separately for each fleet type (buses, trucks, passenger vehicles, specialized machinery). Total CO_2 emissions are then estimated by multiplying the amount of fuel consumed by the emission factor for each fuel type and vehicle type. Information of fuel consumption is estimated based on annual milage and estimated based on available data and number of assumptions proposed in the paper. The proposed methodology for greenhouse emissions inventory for the transport sector allows to analyze available data, recommendations for data collection and a methodology for determining CO_2 emissions from the operation of the transport system with sufficient accuracy of calculations.

Based on these results, it is possible to forecast changes in energy consumption and emissions in the transport sector as a result of various interventions. For example, in Zhytomyr city the results of inventory were used to develop a set of measures, which include updating the rolling stock of electric transport; increasing the energy efficiency of the power grids of the transport system, developing cycling infrastructure.

Keywords: *transport system, greenhouse emissions, SECAP, energy efficiency, CO_2, fuel type, transport categories.*

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1. Introduction

High rates of motorization in recent decades in Ukraine lead to a redistribution of the load between different types of transport within regional transport systems. Such a situation leads to a decrease in the efficiency of the transport systems of cities and regions, a sharp complication of the road situation, a deterioration of traffic conditions, an increase in fuel consumption and, as a result, a deterioration of the ecological situation. On a national scale, emissions from road transport significantly exceed emissions from other types of transport, and account for about 90 % of all transport emissions [1]. The main source of atmospheric air pollution in the central part of cities in Ukraine is road transport.

At the same time, in the last 60 years, the leading countries of the world have seen a significant reduction in emissions of particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HCs), sulfur dioxide (SO_2) and lead (Pb) [2]. Advanced emissions treatment technologies have been developed for petrol and diesel vehicles [3] to meet increasingly stringent regulations, resulting in absolute reductions in fleet emissions despite increased vehicle mileage. As a result of reducing emissions from vehicles and other sources, the air quality in the cities of the USA and Europe has significantly improved [4, 5]. Technical improvement of fuel injection systems allows for more precise control of fuel-air mixtures, necessary for control of unburned hydrocarbons during combustion and efficient operation of catalytic converters. Fuel injection (PFI) was used in more than 90 % of spark ignition (SI) engines sold between 1995 and 2010, and PFI is now being replaced by direct injection (DI), which has increased from 8 % in 2010 to 57 % of new gasoline cars. sold in the USA in 2020 [6]. After the implementation of the control system, which began in the 1970s, evaporative emissions from passenger cars have now decreased by about 100 times [7, 8]. Thanks to

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increasingly stringent emissions regulations, the combined effect of improvements in engine design, fuel systems, catalytic emission control systems, sensor technology and electronic engine management systems, as well as changes in fuel formulations has resulted in impressive reductions in vehicle emissions.

The University of Denver has conducted optical remote measurement of on-road vehicle emissions for 30 years in Los Angeles [9] and over 20 years in Chicago [10]. The remote sensing technique measures the ratio of CO, HC, NO, SO_2, NH_3 and NO_2 to CO_2 in the exhaust gases of individual vehicles as they pass the monitoring equipment. The video camera captures information about the car's license plate, which can be used to determine the car's model year. Research data shows significant progress has been made in reducing emissions over the past 60 years. Remote sensing can be used to identify high-emission vehicles in a fleet for inspection and maintenance.

Fleet turnover, increasingly stringent emission standards (such as Tier 3 in the US, LEV III in California, Euro 6 in Europe and future regulations in the same regions), and widespread adoption of electric vehicles will lead to even lower vehicle emissions and further improvement of air quality.

The methods of collecting, obtaining and analyzing information on the state of atmospheric pollution of Ukrainian cities by motor vehicle emissions are imperfect, high-cost, and do not reflect the modern realities of the development of the motor vehicle complex (in particular, a significant number of cars with diesel engines and outdated rolling stock). The lack of a systematic approach at the stage of accumulation and generalization of information about the share contribution of road transport to the atmospheric air pollution of large cities does not allow forecasting the development of the situation, which causes the low efficiency of the work being carried out [11]. To solve a similar class of tasks in related fields of science and technology, the creation of information systems, which include elements responsible for the behavior of each component of the system, is used. The creation of a monitoring system, which includes the stages of information collection, processing, analysis and visualization, for a comprehensive assessment of the parameters of the Driver – Car – Road system is relevant for the development and adoption of informed decisions in the field of road construction and traffic management, aimed at optimizing the street-road network and minimization of atmospheric pollution.

There are many options for calculating the amount of emissions of harmful substances. The assessment of the state of the air pool in populated areas is carried out by comparing real concentrations with the maximum permissible concentration (MPC). One of the approaches to the control of emissions from transport is defined in the «Sustainable Energy Development and Climate Action Plan» (SEDCAP), which is adopted as part of the «Agreement of Mayors» [12]. The Covenant of Mayors is a worldwide movement bringing together thousands of local authorities who have voluntarily made climate and energy commitments. They are also developing a joint approach to climate change mitigation and adaptation. The signatory cities of the Agreement submit their SEDCAPs, which outline the actions and obligations of the locality to reduce CO_2 emissions by at least 30 % by 2030 compared to the emission levels from the base year. Once every 2 years, a report on the implementation of the Plan is submitted for its evaluation. Cities are also investigating their own vulnerability to climate change and creating their own adaptation projects [13, 14].

SEDCAP combines a complex of strategic projects for the improvement of all spheres and industries of the city (UTC, district, region), taking into account possible sources and mechanisms of their financing, as well as their impact on reducing CO_2 emissions. SEDCAP covers objects in the spheres of both public and private ownership.

SEDCAP foresees qualitative strategic changes of the city (UTC, district, region), its effective energy consumption and reduction of greenhouse gas (GHG) emissions by all involved business entities of the city.

So, *the object of research* is the city's transport system. *The aim of research* is to identify the impact of the functioning of the city's transport system on the amount of greenhouse gas emissions into the environment and to develop a method of estimating emissions for practical use by local authorities to assess activities in the transport sector.

2. Materials and Methods

According to SEDCAP, it is recommended to use the «geographic-territorial» method. In specific circumstances, other methods may be used, for example, «fuel sales», «activities of residents» and «urban methods». Indirect or direct emissions of greenhouse gases are calculated for each energy carrier by multiplying the final energy consumption by the corresponding emission factor. All GHG emissions (direct emissions from fuel combustion and indirect emissions related to the consumption of energy supplied to the grid) arising from transport (both freight and passenger) within the territory of the local authority shall be included in the analysis.

3. Results and Discussion

The agreement of mayors defines the sectors of transport activity, according to the criteria of ownership and operation, as follows: municipal transport fleet; public transport and private and commercial transport.

Total annual emissions in the transport sector [13]:

$$GHG_{emissions} = \\ = \sum_{modes} \sum_{fuels} [emission factor \cdot VKT \cdot Energyintensity], \quad (1)$$

where *modes* – the method (vehicle) of movement/cargo transportation; *fuels* – the type of fuel used by the vehicle; *emission factor* – CO_2 emission factor, which quantitatively measures emissions per unit of activity; *VKT* – annual volume of transport work, which depends on fuel consumption; *Energyintensity* – fuel consumption per unit of transport work (specific consumption of motor fuel).

According to the recommendations [13], the transport fleet should at least be divided into the following categories:

- passenger cars and taxis;
- large-tonnage cars and low-tonnage vehicles;
- buses and other means of transport used to provide public transport services;
- two-wheeled vehicles.

Estimates of greenhouse gas emissions from road transport can be based on two independent data sets: fuel sales and vehicle mileage. If both data sets are available, it is important to check their comparability [14].

Emissions are calculated based on mileage data for each type of fuel for different types of transport.

In accordance with the requirements of the form of the report on the implementation of the Sustainable Energy and Climate Development Plan and the emission inventory, the transport sector is classified according to the type of rolling stock and types of energy consumed.

Rolling stock is divided into:

- municipal park;
- public transport;
- private and commercial transport.

Calculations of emissions from vehicles are based on data on total fuel consumption. The specific heat of combustion and emission factors for each type of fuel are calculated taking into account the specifics of the fuel used by vehicles. The analysis takes into account non-renewable and renewable energy sources. The following types of fuel are taken into account to estimate emissions from the transport sector: gasoline; diesel fuel; liquefied petroleum gas; compressed natural gas; electricity; biofuel (biodiesel, biogasoline, other liquid biofuels).

It is recommended to calculate carbon dioxide emissions from fuel combustion in internal combustion engines based on fuel types and engine types. Carbon dioxide emissions according to this method are estimated as follows. First, the consumption of each type of fuel is estimated by type of transport (cars, trucks, buses, special vehicles). Total CO_2 emissions are then estimated by multiplying the amount of fuel consumed by the emission factor for each fuel type and vehicle type. Annual emissions of CO_2 from fuel combustion of the *i*-th type:

$$Q_{CO_2 i} = BF_i^r \cdot LCV_i \cdot CE_i \cdot CO_i, \quad (2)$$

where BF_i^r – data on the activity of the burning volume of the *i*-th type of fuel per year, t/year; LCV_i – lower calorific value of *i*-th type fuel, MWh/t; CE_i – coefficient of CO_2 emissions, tCO_2/MWh [14]; CO_i – carbon oxidation coefficient in *i*-th type fuel (shows the proportion of burned carbon).

The amount of *i*-th type of fuel burned per year is determined separately for each category of vehicles according to the formula:

$$BF^r = L_y \cdot BF_{100\,km}, \quad (3)$$

where L_y – annual mileage, km; $BF_{100\,km}$ – specific consumption of motor fuel, l/100 km.

The calculation of the annual mileage of vehicles depends on the availability of data and occurs separately for each group of the type of rolling stock. Below is the methodology for determining the annual mileage for different categories.

The most accurate data available to local self-government bodies is information on the fleet of municipal transport. This information can be collected with a level of detail down to the vehicle. Information on the work of the municipal park is provided by the relevant organizations (the information manager) for each vehicle that is on the balance sheet, containing information on:

- type of car/mechanism;
- brand;
- average annual mileage, km;
- specific motor fuel consumption, l/100 km (gasoline, diesel fuel), m^3/100 km (liquefied gas);
- type of fuel (gasoline, diesel fuel, liquefied gas);
- year of state registration;
- engine volume, cm^3;
- machine-hours of operation (for the mechanism): note, current status of the vehicle (for example, write-off from the balance sheet).

According to the basic data collection form, the following types of cars and machinery are distinguished among municipal transport:

- gasoline cars;
- cars on diesel fuel;
- cars on gas;
- gasoline trucks;
- trucks on diesel fuel;
- trucks on gas;
- garbage collection machines;
- garbage disposal machines;
- ambulances;
- police cars;
- road construction machines;
- mobile cranes;
- other machine mechanisms.

Accordingly, CO_2 emissions from the municipal fleet of vehicles are determined depending on such indicators of transport work as the total mileage of vehicles and the total time of operation of mechanisms.

For mechanisms (excavators, mobile cranes, etc.), the main fuel consumption is for the performance of work (machine-hours of operation are fixed), the mileage may be when the special equipment moves independently to the objects of work, or may not be present when transported by motor vehicle:

$$BF^r = L_y \cdot BF_{100\,km} + MH_y \cdot BF_{1h}, \quad (4)$$

where MH_y – machine-hours of work per year, hours; BF_{1h} – specific consumption of motor fuel, l/h.

Fuel consumption is calculated for each type of vehicle:

$$BF_i^r = \sum_{j=1}^{n} BF_j^r, \quad (5)$$

where n – the number of vehicles running on *i*-th type of fuel.

Formula (2) is used to calculate CO_2 emissions from the municipal fleet of vehicles by fuel type.

When determining the volume of emissions from public transport, it is necessary to consider the transport system as a single one independent of the form of ownership of the rolling stock (private or municipal). Public transport can be divided depending on the type of transport into:

- rail (train, tram), subway;
- road transport: trolleybus, bus;
- aviation.

And by type of connection: city, suburban, long-distance (regional and international connection).

According to the guidelines [13], when choosing a fleet of rolling stock to be analyzed, it is necessary to take into account only that part of the movement that takes place in the territory of the city. Moreover, if the trip starts or ends outside the territorial community, it can be ignored. It is advisable to include suburban and intercity transport in the calculation, if measures are planned that affect the indicators of emissions by these types of transport. If rail transport is taken into account, then for

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suburban rail transport, calculations of CO_2 emissions by diesel locomotives and car heating devices are performed separately. Formula (2) is used to calculate CO_2 emissions by diesel locomotives. If the heating device runs on diesel fuel, CO_2 emissions are calculated based on the amount of fuel burned (as for a diesel locomotive).

Data on energy consumption by the respective types of transport are used to calculate CO_2 emissions by urban electric transport. CO_2 emissions by bus transport are calculated based on data on the annual mileage of buses on each route. If the same type of rolling stock using the same type of fuel is operating on the bus route:

$$L_{Pk} = \left[\left(N_{p\ k}^{pd} \cdot l_{mk}\right) \cdot k_{pf} + l_0\right] \cdot D_{wd} + \\ + \left[\left(N_{p\ k}^{bd} \cdot l_{mk}\right) \cdot k_{pf} + l_0\right] \cdot D_{w}, \quad (6)$$

where $N_{p\ k}^{pd}$, $N_{p\ k}^{bd}$ – daily scheduled number of turnovers on the k-th route, respectively, on working days and weekends, units; l_{mk} – length of the k-th route, km; l_0 – daily zero mileage on the k-th route, km; D_{wd}, D_w – working days per year on the k-th route, respectively, on working days and weekends, units; k_{pf} – turnover performance factor on the k-th route:

$$k_{pk} = \frac{N_{pk}^{a}}{N_{pk}^{pl}}, \quad (7)$$

where N_{pk}^{a}, N_{pk}^{pl} – respectively, the actual and planned number of flights per year on the k-th route, units.

If rolling stock of different models using different types of fuel type is operating on the bus route:

$$L_{Pkl} = \sum_{l=1}^{n}\left[\left(N_{p\ kl}^{wd} \cdot l_{mk}\right) \cdot k_{pf} + l_0\right] \cdot D_{wd} + \\ + \left[\left(N_{p\ kl}^{w} \cdot l_{mk}\right) \cdot k_{pf} + l_0\right] \cdot D_{w}, \quad (8)$$

where l – the counter of bus models operating on the k-th route; n – the number of bus models operating on the k-th route, units; k_{pf} – the performance factor of buses of the lth model on the k-th route:

$$k_{pfl} = \frac{N_{pkl}^{a}}{N_{pkl}^{pl}}, \quad (9)$$

where N_{pkl}^{a}, N_{pkl}^{pl} – respectively, the actually completed and planned number of buses of the l-th model operating on the k-th route per year, units.

In the absence of detailed information on the operation of the rolling stock of different models using different types of fuel, with a certain assumption, it is possible to use the formula:

$$L_{Pkl} = \begin{pmatrix} \left[\left(N_{p\ k}^{wd} \cdot l_{mk}\right) + l_0\right] \cdot D_{wd} + \\ + \left[\left(N_{p\ k}^{wd} \cdot l_{mk}\right) + l_0\right] \cdot D_{wd} \end{pmatrix} \cdot k_{rf} \cdot d_l, \quad (10)$$

where d_l – the share of mileage of buses of the l-th model operating on the k-th route in the total mileage on the route:

$$\partial_l = \frac{N_{pkl}^{a}}{N_{pkl}^{pl}} \approx \frac{AD_{kl}}{AD_k} \approx \frac{A_{kl}}{A_k}, \quad (11)$$

where AD_k, AD_{kl} – respectively, the total car-days of operation and car-days of operation of buses of the l-th model operating on the k-th route for a year, days; A_k, A_{kl} – respectively, the total number of buses and the number of buses of the l-th model, which are assigned to the k-th route, units.

Heating (cooling) systems are used in buses to maintain comfortable conditions for passengers and drivers. Additional fuel consumption is taken into account using the correction factor:

$$k_{\Delta BF} = 1 + \frac{\sum_{i=1}^{p}\delta_i \cdot D_i}{100 \cdot D_y}, \quad (12)$$

where δ_i – the value of the allowance for the i-th air temperature interval, % [15]; D_i – the number of days in the year when the i-th air temperature interval took place, which requires heating (cooling) of the bus cabin, units; D_y – the number of days in a year, units.

Then formula (3) takes the form:

$$BF^r = L_y \cdot BF_{100\,\text{km}} \cdot k_{\Delta BF}. \quad (13)$$

Fuel consumption is calculated for each route and fuel type according to formula (13), after which let's find the annual fuel consumption for each fuel type:

$$BF_i^r = \sum_{k=1}^{m} BF_k^r, \quad (14)$$

where m – the number of routes on which vehicles run on fuel of the i-th type.

Formula (2) is used to calculate CO_2 emissions by public transport by fuel type.

Private and commercial transport is the most difficult to determine, because there is no reliable data on the mileage of such transport for the entire city. The annual mileage is determined on the basis of vehicle registration data, fuel sales volumes, and a study of traffic flows and population mobility. Given that passenger and freight transport are very different from each other, they should be calculated separately.

The annual mileage of private passenger cars is calculated by cars running on different types of fuel based on population mobility data:

$$L_i^{pc} = \frac{N_{pop} \cdot k_{mob} \cdot \Delta_a \cdot \bar{l}_n \cdot d_i}{100}, \quad (15)$$

where N_{pop} – the population, persons. Accepted according to [16]; k_{mob} – mobility coefficient (average number of movements per day); Δ_a – percentage of road transport trips as a driver, %; $\bar{l}_n$ – the average distance of a road trip, km; d_i – the share of private cars depending on the type of fuel.

The share of private passenger cars by type of fuel is determined on the basis of vehicle registration data. Provided that these data are not available, it is possible to accept the share of vehicles based on fuel sales data:

$$d_i = \frac{Q_i^{GS}}{Q_\Sigma^{GS}}, \quad (16)$$

where Q_i^{GS} – volume of fuel of the i-th type sold through the gas station, thousand tons; Q_Σ^{GS} – total volume of fuel of all types sold through gas stations, thousand tons.

It is important to note that with an increase in the share of passenger electric vehicles, such an approach will incorrectly reflect the composition of the flow and it is advisable to use data on the registration of vehicles. However, electric vehicles currently make up less than 1 % of Ukraine's transport fleet.

The annual mileage of two-wheeled vehicles (motorcycles, scooters, etc.) is determined similarly by formula (15).

The annual mileage of commercial freight transport is determined by the method of analogy with certain assumptions in the categories: low-tonnage cars, large-tonnage cars.

The total mileage of trucks is calculated for the following categories: light-duty vehicles, heavy-duty vehicles:

$$L_i^{ldt} = L_i^{pc} \cdot \frac{d_{ldt}}{d_{pc}}; \quad (17)$$

$$L_i^{hdt} = L_i^{pc} \cdot \frac{d_{hdt}}{d_{pc}}, \quad (18)$$

where d_{pc}, d_{ldt}, d_{hdt} – respectively, the share of private cars, light-duty trucks, and heavy-duty trucks.

Formula (2) is used to calculate CO_2 emissions by private and commercial transport by fuel type.

Fig. 1 provides the results of calculating annual CO_2 emissions by the main subsystems of the Zhytomyr transport system in 2019.

Interpretation of results. It should be noted that the proposed methodology is based on reliable primary and secondary information and is to some extent unique to the realities of Ukraine.

Practical meaning. The results obtained in the course of the study can be applied in the analysis of the state of atmospheric pollution of cities by transport and used to control emissions from the transport sector, reporting on the implementation of the PDSERK for its assessment.

Limitations of the study. In order to use the results of the research, it is necessary to collaborate with local authorities for the possibility of obtaining secondary and primary information.

The influence of martial law conditions. However, in the conditions of martial law in Ukraine, local authorities have urgent challenges for the survival of cities and limited resources for conducting research on the functioning of transport systems.

Prospects for further research. Since the greatest difficulty is the determination of greenhouse gas emissions from private and commercial transport and it is in this sector that there is a constant significant impact of the external environment, it is necessary to conduct a study of the demand for freight transportation, transport flows and population mobility.

4. Conclusions

A mechanism for recording emissions for the transport sector has been defined, which allows for the analysis of available data, recommendations for data collection and a methodology for determining CO_2 emissions from the operation of the transport system with sufficient accuracy of calculations have been developed. It was determined that the main share of environmental pollution comes from vehicles running on diesel fuel (68.64 thousand tons of CO_2), from private and commercial transport (68 %).

Based on these results, it is possible to forecast changes in energy consumption and emissions in the transport sector as a result of various measures. So, for example, in the city of Zhytomyr, such a set of measures was proposed, including the renewal of electric transport rolling stock; increasing the energy efficiency of the power grids of the transport system, creating bicycle infrastructure (equipment of bicycle parking lots, construction of bicycle paths).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

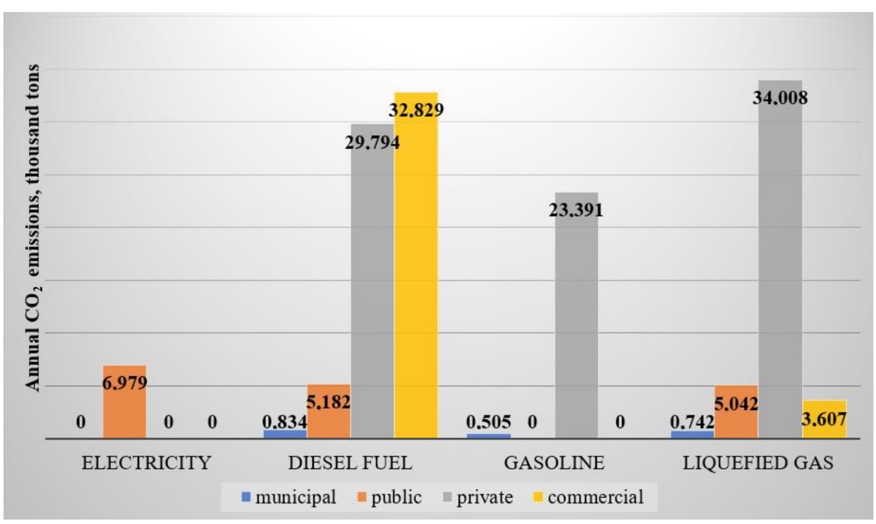

Fig. 1. Annual CO_2 emissions as a result of the operation of the transport system by type of fuel

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✉***Tetiana Tokmylenko,*** *Senior Lecturer, Department of Transport Systems and Logistics, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, e-mail: tetyana@tokmylenko.com, ORCID: https://orcid.org/0009-0006-2542-1452*

Olena Chernyshova, *PhD, Consultant, International Finance Corporation, Vienna, Austria, ORCID: https://orcid.org/0009-0004-9710-3459*

Vitalii Chyzhyk, *PhD, Assistant, Department of Transport Systems and Logistics, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-0518-5246*

✉*Corresponding author*