

EXPERIMENTAL STUDY ON TRANSPORT MODES OF HEAVY TRUCKS

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Abstract. In the present work, a methodology has been developed that allows the study of some parameters of heavy truck traffic. The study uses typical road sections of the suburban road network in which they are determined by average speeds, average fuel consumption and their impact on environmental performance. Specifically, the study was performed on road infrastructure outside the settlements in Bulgaria. In the study, a road infrastructure is divided into three main groups – road infrastructure with roads of the first and second category, as well as highway ones. The research also takes into account the operation of the truck in overcoming both positive and negative slopes. An experimental study was performed for the three types of sections. For them, the speeds of movement in typical time zones, fuel consumption, the speed of the exhaust gases and environmental indicators were measured. The work also looks for the corresponding ratios of the measured parameters for the different routes. The study also measures the exhaust flow rates. Exhaust gas temperatures are also measured at certain points along the route. This is related to the engine operating modes and its direct impact on the environment. The speed of the gases is different in the different speed regimes of the vehicle. The percentage content of the various constituents and their temperatures in the exhaust gases and the knowledge of the velocity of the exit flow make it possible to determine the volumes or quantities of harmful emissions released into the atmosphere. The developed methodology and the performed research can be used for evaluation of the work of the trucks for a certain type of transport network. It allows to determine the efficiency of the vehicle when choosing different transport routes.

Keywords: fuel consumption, road condition, green transport, heavy truck.

Introduction

The work concerns a problem for the passage of heavy good vehicles carrying payloads over 20,000 kg each of them through populated areas. These are transportation in suburban industrial zones, small settlements with roads of the 2nd category and passing through their centres, as well as roads connecting these urbanization formations.

In certain areas of the road network, these roads play an important role in the transportation of goods. Such is the section chosen for the presented study. The passage of one or a group of trucks through these settlements leads to exhaust gas pollution and noise pollution.

Exhaust gases released into the atmosphere are significant in volume and depend both on the number of cars passing per unit of time and on the change in altitude. This means that cars designed to work primarily in highway conditions, where we have a constant mode of operation of the engine, have to work in variable conditions.

Variable operating conditions include the need to operate at a continuous change in speed, resulting in a change in the engine speed and engine modes. The sudden change in altitude or the presence of positive and negative slopes, the low speed of movement and the need for its frequent change, as well as the mandatory stops due to heavy traffic lead to strong non-stationarity of the engine operation.

The reviewed publications concerning the behavior of trucks in terms of fuel consumption and exhaust gas emissions are divided into three main groups.

- *The first group of works comment on the manner of driving the car as an element of ecology.*

Despite the progress in the field of environmentally friendly transport technologies, the possibility of not using vehicles with internal combustion engines, especially in freight transport, is still far away. Road freight contributes significantly to global transport emissions, minimizing fuel consumption for freight vehicles is an important issue.

Freight transport is responsible for around 45% of the total CO₂ emissions caused by mobility. Among them, green driving represents an opportunity that encompasses strategic, tactical and operational decisions and provides suggestions to drivers as well as real-time monitoring of their behavior.

Environmental driving has received considerable attention in the literature. The benefits in reducing CO₂ emissions and fuel consumption are clarified. Lots of research have also reported potential reductions in fuel consumption and CO₂ emissions ranging from 5% to 40% [1-3].

A systematic approach is sought in the work [4], analyzing fuel consumption patterns and factors that affect fuel economy. The main factors that affect fuel economy are presented, including travel-related, weather-related, vehicle-related, roadway-related, traffic-related and driver-related factors are discussed. State-of-the-art fuel consumption models are discussed.

Work [5] examines variables that affect fuel consumption. Environmental driving programs and the impact of (a) heavy and medium-duty vehicles, (b) long-haul freight transport, and (c) the Latin American region are explored, based on statistical analyzes that include multicriteria regression of variables on fuel consumption.

Errors, travel conditions, driver behavior, driver profile and vehicle attributes were investigated. The methodology was applied to a country like Colombia, where road gradients play an important role in fuel consumption.

Works [6-8] comment on the skills of ecological driving of trucks. They are considered an important factor in reducing fuel consumption. An energy approach is used to enable an objective and dynamic assessment of green driving skills. This is by taking into account integral indicators directly characterizing non-productive energy costs. Experiments are being conducted with a certain number of truck drivers. As a result of the training, a reduction in fuel consumption by an average of 13.6% was achieved.

In the work [9], the possibility of building models for ecological driving of the car related directly to the characteristics of the engine is investigated.

- *The second group of works concerns reducing fuel consumption by choosing an appropriate route.*

In works [10-13], the approach for evaluation and selection of different travel routes is applied. If the requirement for lower fuel consumption and lower exhaust gas values is applied, they become eco-routes. Road transport is one of the main sources of greenhouse gas emissions. One way to reduce energy consumption and alleviate this environmental problem is to develop eco-routes.

The vehicle route planning problem focuses on route optimization based on traffic and environmental data. Some of the works suggest the development of navigation systems.

In these works attention is paid to the behavior of truck drivers. Drivers typically choose routes that minimize travel time or total cost. This can lead to different decisions when comparing costs. In particular, significant energy and air quality improvements can be achieved when drivers use slower routes, even though they require additional travel time.

Work [14] comments on the choice of eco routes when entering large cities and the benefits of using eco routes there. It is also commented that the reduction in fuel consumption is reduced by 3.3% and 9.3% compared to the usual travel time. The configuration of the transport network is also commented on as an important factor in determining fuel consumption.

In the work [15], several methods for determining a more sustainable distribution of traffic flows are investigated. In response to rising energy costs and increased environmental concerns, eco-route choices can be individually provided through intelligent navigation systems that allow multiple vehicle routing options designed to minimize air pollutants. Several routes were investigated using a GPS system and determinations were made of their level of environmental friendliness. Two different approaches were tested to estimate emissions (CO₂, HC, CO, NO_x).

- *The third group of works includes only one study [16] done in the northern border regions of the Republic of Bulgaria. This study is not related to the evaluation of the environmental friendliness of road transport, but to the organization of traffic in the northern border regions. They are the object of research in the present work.*

The purpose of the present work is to obtain real data on the behavior of heavy highway vehicles when driving in small settlements and the roads that connect them. Obtaining data on exhaust gases and their emissions, as well as their quantity and temperature, is an important factor for environmental performance in these urbanized areas.

Materials and methods

Methodology of conducting the experiment. Truck fuel economy and environmental performance tests are large in volume, energy-intensive, expensive and difficult to perform. The work seeks indicators for the assessment of pollution in the northern border areas when highway trucks pass through settlements with variable altitude.

Selection of road sections

The study was conducted on a specific section of the road network. This road section is located near one of the border exits of Bulgaria. The road network on which the measurement is carried out contains highway-type roads, suburban roads, roads connecting small settlements and passing through small settlements.

The road sections are of mixed type in terms of altitude. They contain slopes of varying intensity and flat sections. The road surface is well maintained. It is of mixed type over 80% asphalt and in small sections pavement. Measurements are made in both directions of the selected path. During the measurement, the surface of the road surface is dry.

The route must also include roads with pavement in good condition, asphalt in good condition and worn pavement and asphalt surfaces. Worn pavements are those with reduced traction properties and with the appearance of waves on them characteristic of the road network.

When measuring indicators such as fuel economy and ecological ones for trucks, in global practice there are no firmly established standards for road conditions. One of the characteristic choices of road surfaces is that of the EUROPEAN TRUCK CHALLENGE test trials. The following road categories are offered in these test trials: highway section – general traffic, highway section – easy, highway section – medium difficulty, highway section – difficult, mountain climb, traffic at a constant speed of $82 \text{ km}\cdot\text{h}^{-1}$, intercity two-lane road.

The positive and negative gradients need to be typical of the road network. The authors wanted to use the climatic conditions of the area without including the extreme conditions in the study. The article does not consider the behavior of the truck at temperatures below $10 \text{ }^{\circ}\text{C}$ and high air humidity and at temperatures above $30 \text{ }^{\circ}\text{C}$ and low air humidity. The temperature of the road surface during the measurement should not be lower than $16 \text{ }^{\circ}\text{C}$ and not higher than $28 \text{ }^{\circ}\text{C}$. In the summer period, temperatures in the studied area reach $38\text{-}40 \text{ }^{\circ}\text{C}$.

The length of the road section is not commented on. Sections are required to be typical of the area. Typical driving speeds for a given road section are: for a highway section, typical speeds are up to $89 \text{ km}\cdot\text{h}^{-1}$. The speed limiter of this type of vehicle is set to this speed.

Another characteristic speed of the truck is the speed of passing through the settlements and the roads that connect them. The speed limit there is $50 \text{ km}\cdot\text{h}^{-1}$.

External atmospheric conditions

The tests were conducted in the month of November. The measurements were made in the time range 10 am to 16 pm. The weather forecast during the hours in which the test was conducted is in the range of $16\text{-}20 \text{ }^{\circ}\text{C}$. Humidity is within normal limits. It is recommended that the wind speed be $0 \text{ km}\cdot\text{h}^{-1}$. During the test, the wind speed was below $0.5 \text{ km}\cdot\text{h}^{-1}$.

Measured indicators

Experimental studies include real-time measurement of six indicators. The measurement includes the measurement of the speed of the vehicle V_{truck} , the change in altitude $H_{altitude}$, the speed of the exhaust gases V_{gas} , the instantaneous fuel consumption Q , the instantaneous emission values NO_x , CO , CO_2 , the temperature of the exhaust gases $t_{ex.gas}$, the engine speed n .

During the experiment, the driver follows the flow of cars in traffic, performs the necessary maneuvers in accordance with traffic rules. The driver maintains a speed close to the maximum allowed for the individual sections ($50 \text{ km}\cdot\text{h}^{-1}$ for populated areas or $90 \text{ km}\cdot\text{h}^{-1}$ for the highway).

The work also examines one specific indicator. This is the speed of the gas flow in the exhaust pipe of the vehicle. The acceleration time greatly affects the quantity and quality of the exhaust gases. This

is the reason for examining the exhaust emission rate. The speed of the gases when accelerating the vehicle is directly related to the amount of harmful emissions entering the space. The exhaust gas volume can be calculated as follows

$$W_{ex, gas} = SV_{gas}T_{acc}, \quad (1)$$

where S, m^2 – cross-sectional area of the outlet pipe;
 $V_{gas}, m \cdot s^{-1}$ – speed of the exhaust gases;
 T_{acc}, s – time of passage of the gases.

Knowing the percentage content of the components in harmful emissions, their quantity can be obtained.

Measuring Equipment

Movement speed and altitude change are measured with a GPRS system. In addition, the speed of movement is controlled by the tachograph of the vehicle.

The exhaust velocity is measured with a Testo 6351 differential pressure transmitter (Pitot tube). The measurement accuracy is 0.5%. If the rate of passage of the gases is known, the corresponding volumes passed by them can be determined, and according to the percentage content of each of the gases, their absolute value can be determined.

The current fuel consumption is reported by the vehicle's on-board computer, which is previously compared with another meter of real values of the fuel consumed. The engine speed is also measured in the same way. Service equipment is used to measure emissions. Emissions released into the environment are reported in volume percentages as follows: CO₂, CO, O₂, % per 100 units. Hydrocarbons CH and nitrogen oxides NO_x are measured in units of ppm (% per 10000 units). Exhaust gas emissions are measured with a TEXA gas analyzer and the exhaust gas temperature is measured with a thermocouple. For recording some of the engine parameters, an on-board diagnostic system Delphi Technologies, model Delphi DS 150E, is additionally used.

The experiments were carried out in a driving variant using the automatic gearbox and mechanical gear shifting.

Results and discussion

The experiments were conducted in the region of the city of Montana, Bulgaria. The area is characterized by a sharp change in altitude. The area is a border area and is close to a road with the European marking E79. Trucks connected with the transport of goods from Bulgaria and the southern and neighboring countries to Eastern and Central Europe pass here. A large number of these cars pass through small towns with narrow streets. The selected route is shown in Fig.1.



Fig. 1. Area around the city of Montana: description of the route along which the experiment was conducted

The routes are marked with indicators from M1 to M8. As it can be seen from the graph, the route is travelled in a straight and reverse direction. Measurements were made four times and the results were averaged.

The experiments were carried out with a truck in combination with a semi-trailer (Fig. 2). The length of the transport unit is 18.7 meters. The mass of the two means of transport without load is 16285 kg, and the full mass with load is 44000 kg. The tractor is a truck with three axles and wheel formula 6x2, emission standard EVRO 5. The engine power is 300 kW. The tractor is equipped with a 12-speed gearbox, working in automatic and manual mode. The semi-trailer has two axles with a central location of the axles. The experiments were carried out with a load on the tug and pluremark 50% of the full permissible load.



Fig. 2. Transport unit with which the experiment was carried out

The connection diagram of the measuring equipment is shown in Fig. 3, it shows the connections between the receivers for measuring the speed of exhaust gases (pitot tube), their composition measured by the gas analyzer, the GPRS signals for measuring the speed of the vehicle and altitude, and thermocouple for measuring the temperature of the exhaust gases.

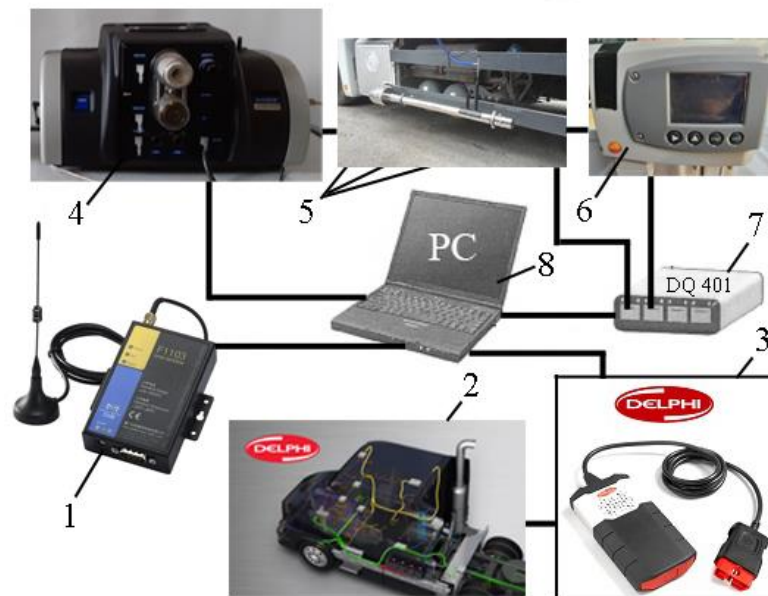


Fig. 3. Schematic diagram for measuring: 1 – GPRS (General Packet Radio Service) for measuring movement speed and altitude change; 2 – heavy-duty truck with which the road experiments are carried out; 3 – delphi truck diagnostic tool; 4 – gas analyzer; 5 – one tube for reaching the gases to the gas analyzer and another Pitot tube for measuring the speed of the exhaust gases and thermocouple for measuring the temperature of exhaust gases; 6 – pulse signal converter from Pitot tube; 7 – DQ 401 – data acquisition; 8 – PC – personal computer with the necessary software for data processing

Below in the work in Fig. 4, Fig. 5 and Fig. 6, the actual measurements of the indicators for the section M3 are presented. in graphic form. Section M3 is important for comparative measurements.

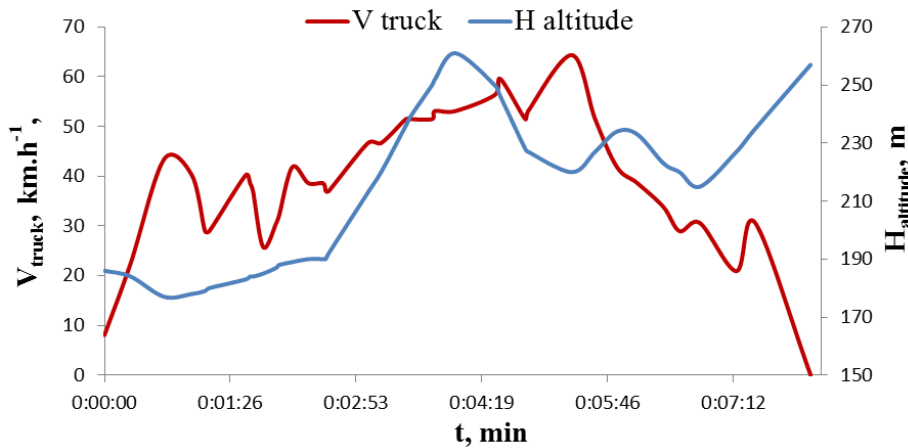


Fig. 4. **Route M3. Altitude of the section and truck speed.** Movement between populated areas by passing through them with the maximum permitted speed of the truck up to 50 $km \cdot h^{-1}$

The results of the measurements in it will be compared with the M1 section, movement in the suburban industrial area with small road gradients, and M6, which is a highway. In the M6 section, the vehicle moves at a speed of 80-85 $km \cdot h^{-1}$.

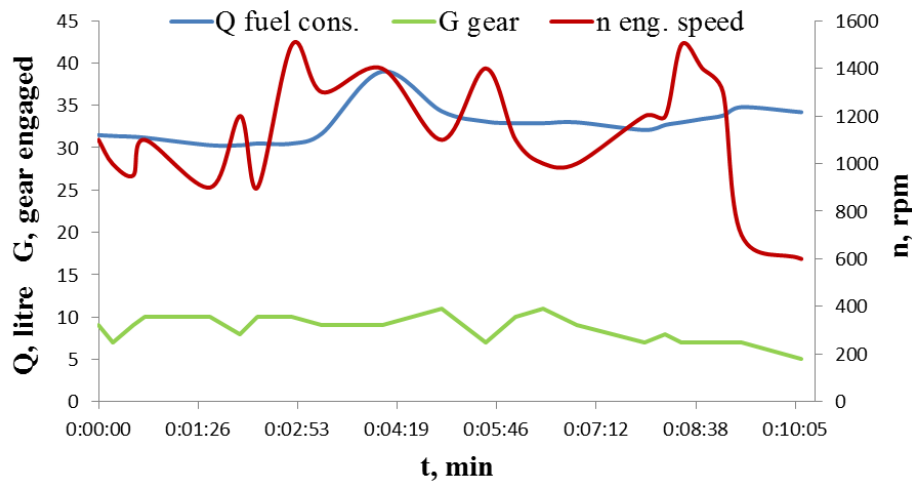


Fig. 5. **Route M3. Fuel consumption Q and engine speed n**

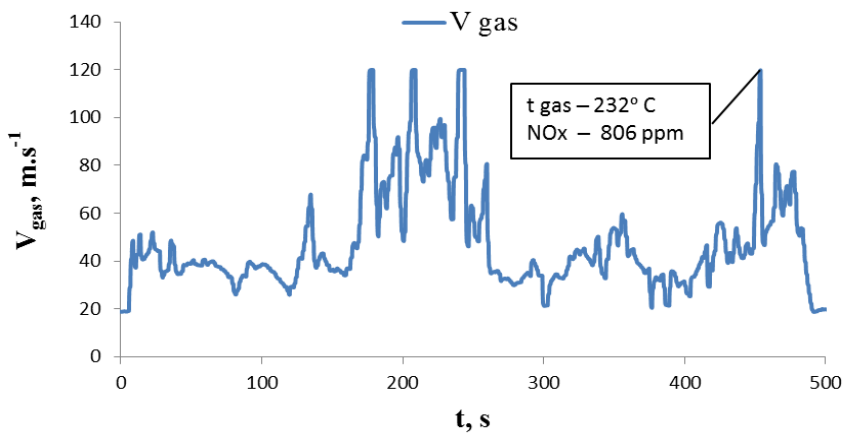


Fig. 6. **Route M3. Speed of exhaust gases:** the graph also shows instantaneous values of nitrogen oxides NO_x and exhaust gas temperature $t_{ex. gas}$

The M3 route is characterized by the fact that it passes through two settlements connected by a second category road. The difference in altitude is more than 100 meters. This is also the reason why the movement of the cars is in the non-stationary regimes.

Table 1 and Table 2 show the averaged results of the measurements of the eight routes.

In Table 1, the indicator H_{up} refers to the largest increase in altitude for a given section of the route, where the truck is moving on a road with a slight gradient.

Table 1 shows the difference in altitude overcome by the truck. The largest is the one for the M6 route (stationary traffic on a highway section and traffic at over $80 \text{ km}\cdot\text{h}^{-1}$). The difference in altitude is smaller for the M3 section (non-stationary movement through urban areas and speed below $50 \text{ km}\cdot\text{h}^{-1}$).

Table 1

Measured car parameters and road altitude

Route	V truck, average, $\text{km}\cdot\text{h}^{-1}$	H_{up} altitude, m	n engine speed average, min^{-1}	Q fuel consumption average, l per 100 km	$t_{ex. gas}$, $^{\circ}\text{C}$
M1	36.56	12	956	36.38	142
M2	43.02	76	1122	32.26	202
M3	40.14	84	1155	32.63	208
M4	44.64	38	1174	33.35	196
M5	41.11	54	1060	32.77	212
M6	81.90	134	1132	32.73	252
M7	81.70	24	1090	32.32	183
M8	31.11	16	878	29.37	155

Table 2

Measured parameters of exhaust gases

Route	V_{gas} average, $\text{m}\cdot\text{s}^{-1}$	$W_{ex. gases}$ for 505 seconds, m^3	NO_x , p.p.m. average	CO , % average	CO_2 , % average
M1	36.144	51.60	354.60	0.0157	4.357
M2	45.11	64.55	565.00	0.0380	5.820
M3	47.116	67.27	559.50	0.0617	4.883
M4	42.896	61.24	412.75	0.0520	4.520
M5	44.897	64.10	326.00	0.0083	4.650
M6	63.034	90.00	409.33	0.0050	5.038
M7	42.142	60.17	458.29	0.0143	5.000
M8	33.725	48.15	330.00	0.0050	3.025

The pollution (Table 2) from the exhaust emissions, the volumes emitted and the temperature measured at the end of the exhaust pipe in the section M3 are measurable with those of the section M6.

Figure 7 shows a comparison of the exhaust gas volume and NO_x average values for specific driving routes M1, M3 and M6.

From the results presented in Table 1 and Table 2, routes M1, M3 and M6 were selected for comparison. These routes are specific in terms of their traffic indicators: M1 is truck traffic in an urban industrial zone and has small changes in altitude; M3 is truck movement in urbanized areas and the roads connecting them. M3 has greater elevation changes; M6 is movement of the truck in highway conditions, in a non-urban environment and with the greatest changes in altitude.

The analysis of the obtained results shows that routes connected to urbanized territories, but with a small difference in altitude, such as M1, pollute the environment around them the least. In this case, the trucks emit the smallest volume of exhaust gases and the lowest emission values. The M3 route, which is also in urbanized areas, but with greater differences in altitude, shows an increased volume of exhaust gases and emission values. On the M6 route, which is a motorway, the truck runs with optimal engine performance and a high gear engaged in the transmission, which is reflected in the volume of exhaust gases and lower emission values than the M3 route. A comparison of this is shown in Fig. 7.

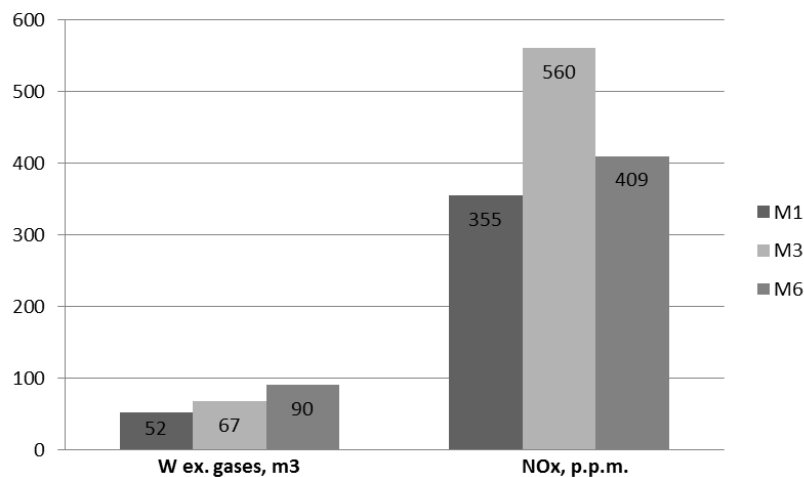


Fig. 7. Volume of exhaust gases and average values of nitrogen oxides NO_x for routes M1, M3 and M6

The research is based on comparative analysis. That is, the accuracy and measurement errors are the same for all measurements made and depend on the equipment used, described above. Average values of the measurements are presented.

In the review of the works of other authors related to the subject under consideration, it was found that the following parameters are not taken into account: exhaust gas volumes are not measured, changes in altitude and the influence on emission volumes are not taken into account.

Conclusions

The work proposes a methodology for the assessment of roads of the second category, which are used for the passage of highway vehicles. The change in the operation of their engines in real non-stationary modes is evaluated, taking into account the change in the amount and composition of emissions in the exhaust gases.

1. As a result of the experiment, the vehicle's ecological indicators (CO , CO_2 , NO_x , V_{gas} , $W_{ex. gas}$) and their impact on the environment were measured along predetermined routes for road sections from M1 to M8. On the basis of expert assessment, sections M1, M3 and M6 were determined for comparison. Based on the comparison, an assessment of the impact of one truck on an urbanized area was made. The increase in the volume of exhaust gases for the M3 route compared to the M6 is 25% more for M6. This is due to the higher speed of traffic on the M6 route. The comparison of the NO_x values for the two routes shows a tendency of reduction for route M6 compared to M3 by 27%, which is due to optimal engine operation and a high gear engaged in the transmission.
2. The exhaust gas volume parameter $W_{ex. gas}$ is entered. Together with the temperature of $t_{ex. gas}$ gases and the number of trucks passing per unit time through populated areas, a better assessment of the environmental impact of exhaust gases there can be obtained. The passage of more lorries through a populated place with the shown emission parameters and their indicators needs to be regulated by frequency of passage of trucks.
3. The research makes it possible to make a preliminary test evaluation of trucks and routes to be defined as "green".

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Author contributions

Methodology, E.S. and L.K.; software, E.S.; validation, E.S. and L.K.; formal analysis, E.S., E.D. and L.K.; investigation E.S., E.D. and L.K.; data curation, E.S. and E.D.; writing review and editing, E.S.

and L.K.; visualization, E. S.; All authors have read and agreed to the published version of the manuscript.

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