EXPERIMENTAL STUDY OF TRANSPORT FLOWS IN BIG CITIES

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Abstract. In the present work a methodology has been developed to study some parameters of traffic in characteristic sections of urban infrastructure. For this purpose, the average driving speeds, average fuel consumption and their impact on environmental performance are determined. The traffic in the road infrastructure of the capital of Bulgaria - Sofia has been studied. In the study, the road infrastructure is divided according to the degree of traffic load into three main groups. These are transport sections in the center of the city with high traffic during heavy traffic hours, sections with medium load and sections of highway type. An experimental study was performed for the three types of sections. For these sections the speeds of movement in typical time zones, fuel consumption, the speed of the car's exhaust gases and ecological indicators were measured. The work introduced a coefficient of stay, reflecting the ratio of the time in which the car was moving at a speed below 1 $km \cdot h^{-1}$ or was at the traffic lights to the total travel time in the section. This coefficient is introduced to determine the traffic load in the respective sections. The study of the speed of cars in these sections is also important in the case when conventional cars are replaced by those that use electricity (electric cars). The test performed to measure the exhaust gas flow rate depends on the engine operating modes. The speed of the exhaust gas discharge has a direct impact on the environment. The speed of the gases is different in the different speed regimes of the car. The percentage of the various components in the exhaust gases and the knowledge of the outflow rate make it possible to determine the volumes or quantities of harmful emissions emitted into the atmosphere. The developed methodology and the performed research can be used for assessment of the transport network in busy urban areas, correction of the results obtained by WLTP or NEDS and prognosis. The dimensionless coefficient is introduced in the work for the first time. It is the ratio of the time in which the car is at rest (speed below 1 $km \cdot h^{-1}$) to the total time for passing the relevant section. The coefficient reaches the road sections loaded in certain time zones to values 0.40-0.45. Another indicator that is being introduced for the first time is the volume of exhaust gases.

Keywords: traffic, transport, flows, speed, emissions.

Introduction

The proposed research includes a study of specific sections of the urban road network. These are the roads that at certain times of the day become a cramped place for cars. The speed of movement is extremely low. Harmful emissions are atypical and difficult to determine because the operating modes of internal combustion engines are highly nonlinear.

The need to reduce the negative impact of cars on the environment has become an important factor in the development of the industry. In recent years, standards have been adopted with increased requirements for car emissions. Efforts are currently being made to introduce emission testing procedures that include the operating range of the engine used in real driving conditions.

The conditions that affect the level of emissions occur under real driving conditions. The results of road tests are not always identical to those obtained during emission tests. The differences in results are due to factors such as: environment (variable temperature, atmospheric pressure, humidity, wind speed, rain, snow, etc.), road condition, traffic intensity, driver behavior - aggressive, neutral, environmentally friendly driving.

Publications on these issues can be divided into the following groups.

- The first group of works is dedicated to the creation of laboratory test conditions that will most reliably recreate the road conditions, emissions and fuel consumption are taken into account. These are tests like NEDS and WLTP. Such are the works [1-5]. This way of research is necessary in order to create equal conditions in which to compare cars.
- The second group of works concerns specific research in road conditions. These tests are needed to adjust, if necessary, laboratory tests or to obtain results for situations other than laboratory tests. In [6] the authors consider and conduct road tests on urban and extra-urban routes and propose the introduction of correction factors for the obtained emissions. In [7] the authors propose conducting road tests on three routes to obtain real-world emissions. A similar idea is used by the authors of the work [8]. Here are four routes (urban, suburban, mixed and hilly) of Hong Kong. The article analyzes road emissions and fuel consumption of a Euro 4 petrol car

driven by them. The effects of changes in road slopes and traffic conditions on emissions and fuel consumption are shown. In [9] a method is proposed for determining the driving cycles of cars in urban traffic for the center of Naples. Fuel consumption and test car emissions on certain urban routes were measured in [10], the indicators of two cars equipped with different engines (petrol and diesel) in real traffic on a test route on the highway are investigated.

- The third group of works related to vehicle emissions is devoted to other methods. In [11] an overall estimate of the emissions of cars of different types in the countries of the European Community is made. In [12] the authors use calculation procedures to obtain the amount of exhaust gases.

The following characteristic speeds are known to be compared to the speed of car traffic in large cities. This is the average speed of pedestrians 5 km·h^{-1}, the average speed of cyclists 15-20 km·h^{-1}, which in the presence of wide bike lanes can reach 30 km·h^{-1}. Here it is necessary to add the speed of electrified two-wheeled vehicles such as bicycles, scooters and others, which is 30 km·h^{-1}. The study of car traffic in large cities requires the definition of different time zones and different city-specific road sections, the study of road sections with intensive traffic in some characteristic parts of the day, when the traffic is intensive, as the studied values can be assumed average speed for passing a typical road section and time for passing the section. These indicators can be compared with those of other urban road sections. These parameters do not allow for comparison on one indicator such as the movement of the car at speeds below 1-2 km·h^{-1}, these are speeds at which the car is practically at rest.

A speed of 1-2 km·h^{-1} is important as an indicator of the throughput of these sections during heavy traffic. Studying this type of section is important because drivers waste time in their cars, the environment is saturated with emissions from exhaust gases and their components.

According to a publication and study by the DPA (Deutsche Presse-Agentur GmbH), drivers in major world capitals lose more than 100 hours in one year. For example, the lost time in traffic of German drivers is the smallest.

The research discussed in the present paper addresses a specific problem of urban traffic. This is a study of traffic jams in certain time zones. These studies are not well represented in NEDS and WLTP test cycles. In WLTP in the part concerning low speeds up to 50 km·h^{-1} there is a better correspondence between the real processes and those filmed in real conditions.

The aim of the present study is to obtain real data on congested routes from the urban road network and on their basis to propose indicators for assessing their load as traffic and load as emissions from cars.

Materials and methods

The presented work proposes specific indicators to show more accurately the phenomena occurring in heavy traffic. In this study new indicators to assess the traffic are proposed.

The first specific indicator is related to the time lost by drivers in a section of road. This can be represented by the time spent in this section T_{stop}, s or driving at extremely low speeds (less than 1 km·h^{-1}). Another indicator that can assess the road section is the dimensionless coefficient which is the ratio of the time in which the car is at rest (speed below 1 km·h^{-1}) relative to the total time for passing the relevant section T_{sum}, s.

$$K_{stop} = \frac{T_{stop}}{T_{sum}}, \tag{1}$$

where T_{stop} – time in which the driver is traveling at a speed of less than 1 km·h^{-1}, s;
T_{sum} – total time to cross the section, s.

This indicator is proposed for the first time in this study.

If it is necessary to assess the possibility of a road section by bicycle or other alternative means, a similar factor can be studied as the ratio of the time the car travels at a speed lower than that of the bicycle to the total travel time.

The behavior of the car when passing sections with different loads is different. It depends on the driver’s driving style. The driver is dependent on the behavior of the transport flow. The intensity with which it moves, stops and accelerates the flow affects both the speed of the car and the speed of the gas flow in the exhaust pipe.

The second specific indicator is the speed of the gas flow in the exhaust pipe of the car. The acceleration time of the car strongly influences the quantity and quality of exhaust gases. This is the reason why the rate of exhaust emissions is being studied. The speed of the gases when accelerating the car is directly related to the amount of harmful emissions entering the space. The volume of exhaust gases can be calculated as follows

$$W_{ex.gas} = S \cdot V_{gas} \cdot T_{acc}, \tag{2}$$

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

This indicator is proposed for the first time in this study.

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

The paper considers different variants of the car movement, acceleration with different intensity and from different initial speeds, uniform movement at different speeds, operation of the engine at extremely low speeds of the car.

Methodology of the experiment

- **Selection of road sections.** The study was conducted on typical sections of the city road network of Sofia. They are characterized by intense traffic in the time zone 17-18.30 o'clock and 8-9 o'clock. The road sections have been chosen to be horizontal. This is necessary so that slope resistances are not taken into account. The sections have slopes of up to 1%. To compensate for the slopes, research is conducted in both directions. The studied sections have a total length in both directions 3.0-4.6 km. The road surface is asphalt with a well-maintained surface.
- **External atmospheric conditions**. The tests were performed at an outdoor temperature of 18-25 ºC. Normal humidity. There is no wind, which eliminates frontal air resistance,
- **Measured indicators.** Experimental studies include real-time measurement of four parameters. This is the speed of the car V_{car}, $m \cdot s^{-1}$. The maximum speed has been adopted in accordance with transport legislation. The maximum speed for city traffic is 50 $km \cdot h^{-1}$, and for traffic on city highways is 80 $km \cdot h^{-1}$. The speed of the exhaust gases V_{gas}, $m \cdot s^{-1}$ and the fuel consumption Q, $l \cdot h^{-1}$ are also measured. Additionally, the volume of exhaust gases $W_{ex.gas}$, m^3 is calculated. During the experiment, the driver follows the flow of cars in traffic, performs urgent maneuvers and is an integral part of traffic in compliance with traffic rules.
- **Measuring equipment.** Travel speed is measured with a Peiseler fifth wheel. The speed of the exhaust gases from the engine is measured with a differential pressure transmitter – testo 6351 (Pitot tube). Fuel consumption is measured by a flowmeter PLU 116H, and emissions are measured with a TEXA gas analyzer.
- **Consistency in the experiment.** After selecting the characteristic sections, the time zones in which the experiment is conducted are selected. Visually and by counting the passing cars per unit of time, the hours in which the experiments are conducted are determined. These are 8-9 o'clock, 10-11 o'clock, 12-13 o'clock, 15-16 o'clock and 17-18.30 o'clock.

Results and discussion

The experiments were performed on all working days of the week. In each of the time zones 4-6 experiments were conducted in both directions and the results were averaged. The main indicators are the speed of the car and the flow rates of the exhaust gases. The difference is only in the percentage of harmful emissions in the content of the emitted volumes of harmful emissions.

The experiment was conducted with a light truck with a diesel engine, Fig. 1. The ecological category of the vehicle for conducting specific measurements and subsequent analyzes does not affect the main results of the study. The main indicators are the speed of the car and the flow rates of the exhaust gases. The difference is only in the percentage of harmful emissions in the content of the emitted volumes of harmful emissions.

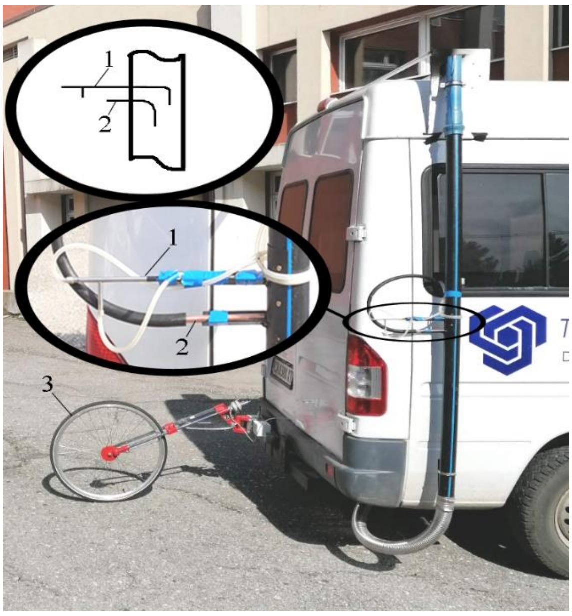

Fig. 1. **General appearance of the installed receivers:** 1 – Pitot tube; 2 – tube for exhaust gases; 3 – fifth wheel

The connection diagram of the measuring equipment is shown in Fig.2.

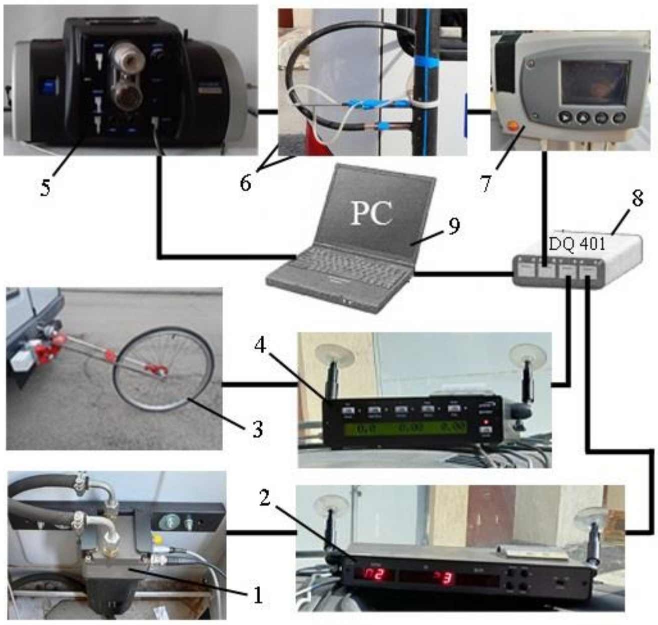

Fig. 2. **Schematic diagram for measuring:** 1 – flowmeter; 2 – pulse signal converter from the flowmeter; 3 – fifth wheel for measuring speed; 4 – fifth wheel signal convert; 5 – gas analyzer; 6 –tube for reaching the gases to the gas analyzer and the Pitot tube for measuring the speed of the exhaust gases; 7 – pulse signal converter from the Pitot tube; DQ Hotinger digital converter; PC – personal computer with the necessary software for data processing

Figure 2 shows that the electrical signals from the fifth wheel, the Pitot tube and the flow meter are fed to the analog-to-digital converter DQ Hotinger. It converts signals from analog to digital and they are processed by the computer. The signals from the gas analyzer with the help of a specialized program are fed directly to the computer.

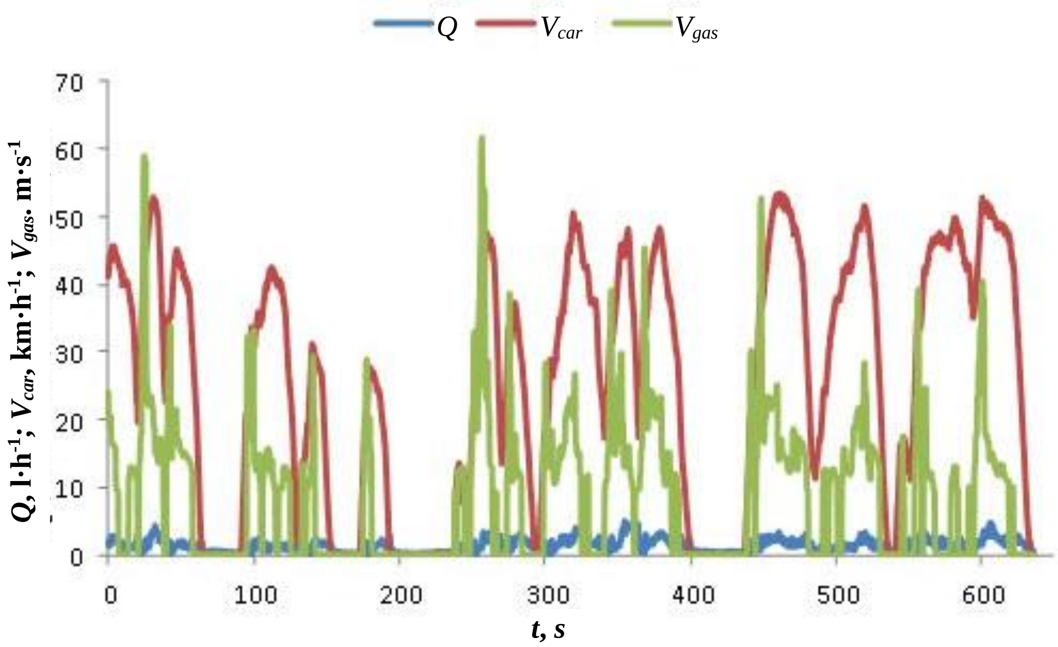

Fig. 3. **Passing at 3 pm through a road section with a strong traffic load:**
Q – fuel consumption; V_{car} – speed of the car; V_{gas} – speed of the exhaust gases

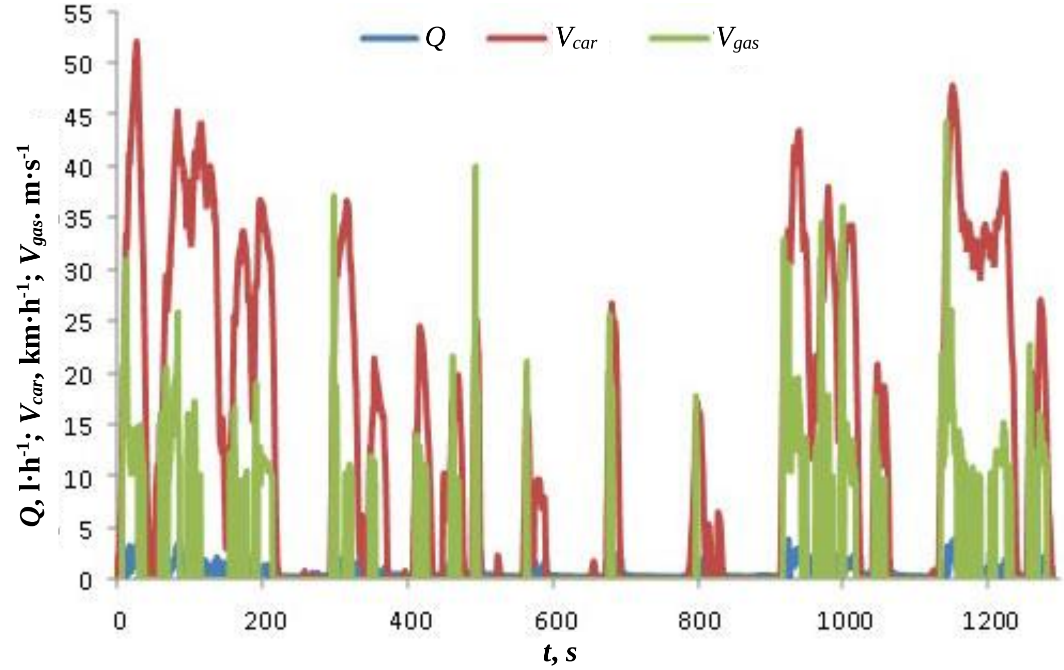

Fig. 4. **Passing at 5 pm to 6 pm through a road section with a strong traffic load:**
Q – fuel consumption; V_{car} – speed of the car; V_{gas} – speed of the exhaust gases

Figure 3 and Figure 4 show two typical records of a section with a heavy traffic load. One of the recordings was made at 3 pm and the other at 5 pm to 6 pm. The following differences can be seen visually. The time to cross the same section in length is almost twice as long in the time zone 5 pm to 6 pm. The second feature is that the car, following the traffic flow, accelerates in different ways in both cases.

The test results are processed and data on the coefficient of stay K_{stop} are obtained, Fig. 5. Formula (1) is applied to determine this coefficient.

Figure 5 shows how traffic at different times of the day affects K_{stop}. Four road sections are considered. The first is a section of downtown. The second is from this part of the city called the "wide center". The third section reflects a moderately busy area, and the fourth section refers to a city highway. Sections of road with a coefficient of stay less than 0.2 have good possibility.

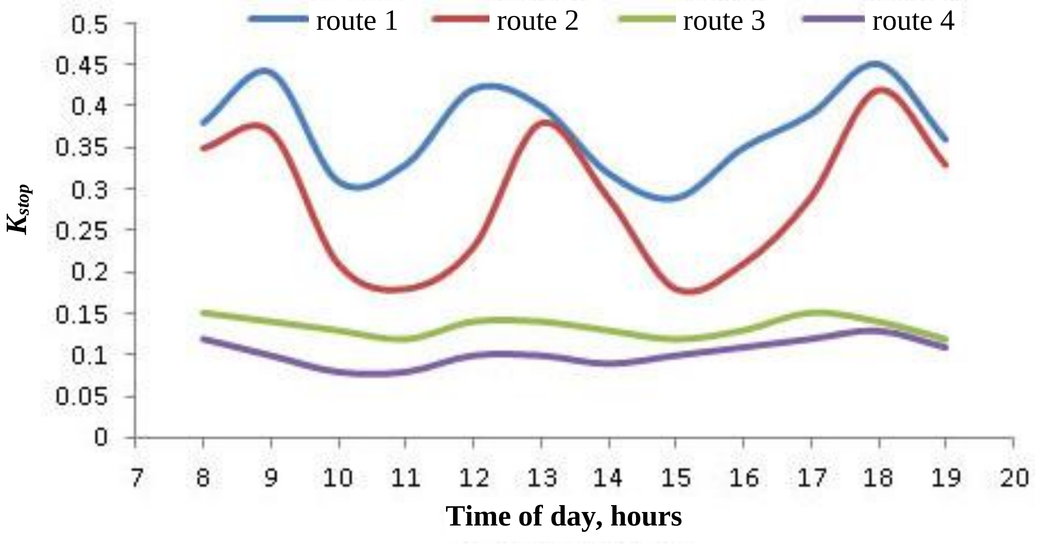

Fig. 5. **Change of the coefficient K_{stop} at different times of the day for four road sections:** route 1 – section of downtown; route 2 – wide center; route 3 – moderately busy area; route 4 – city highway

The studied parts of the urban road network are characterized by strong nonlinearity of the change of speed. This nonlinearity is due to the uneven supply of fuel. The speed of fuel supply affects the speed of the exhaust gases. In order to determine the different regimes, the emissions in the most repetitive accelerations from the graphs in Fig. 3 and Fig. 4 are used. Instantaneous emission measurement at acceleration from 0 to 60 km·h^{-1} is shown in Fig.6.

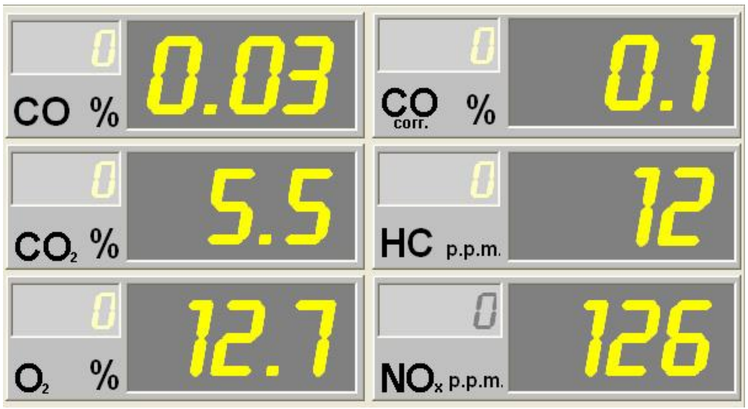

Fig. 6. **Screen view of the gas analyzer interface with instantaneous emission values when accelerating the vehicle from 0 to 60 km·h^{-1}**

The results of the measurement of the gas velocity and the corresponding instantaneous emission values at typical modes are shown in Table 1. The data obtained for V_{gas}, T_{acc}, and knowing S, allow to determine the volume of exhaust gases $W_{ex.gas}$ by formula (2).

The volume of exhaust gases is a sufficiently accurate indicator of the participation of cars in environmental pollution. In its values it depends on the size of the internal combustion engine, and in quality on the environmental category of the car.

Based on the obtained results, some average values were calculated. For the presented records in Fig. 3 and Fig. 4 average values of the vehicle speed V_{car} are reported. The average speeds of the car are 13.2 km·h^{-1} for driving in 5 p.m. and 25.7 km·h^{-1} for driving at 3 p.m. The average speed of the exhaust gases in the first case is 4.2 m·s^{-1}, and for the second case it is 7.8 m·s^{-1}. These are average gas speeds only when the car is moving. Gas speeds in case of downtime are not taken into account. The downtime in the case of Fig. 4 for movement in the time zone 5 pm is over 40% of the total time for passing the section. Although the average value of the gas velocity in Fig. 3 is higher, taking into account the residence time of the second case of Fig. 4, more exhaust gases are discharged into space than in the case of Fig. 3. One of the environmental pollutants is not only the components of the exhaust gases, but also the warming of the air in these areas of heavy traffic. This is best taken into account with the exhaust gas volume parameter $W_{ex.gas.}$

Table 1

Exhaust gas parameters at different vehicle acceleration and instantaneous emission values

V_{car}, km·h^{-1} from…to…	T_{acc}, s	V_{gas} average value, m·s^{-1}	$W_{ex.gas}$, m^3	CO, %	CO_2, %
0-46	25	15	1.060	0.04	6.2
12-40	25	17	1.202	0.03	5.9
0-31	15	33	1.400	0.03	5.4
15-38	15	18	0.763	0.02	6.3
12-58	35	18	1.781	0.02	6.0
18-48	10	38	1.074	0.03	5.3
22-51	10	36	1.018	0.08	5.1
15-28	15	16	0.679	0.07	5.3
2-26	15	18	0.763	0.06	5.9
15-35	15	18	0.763	0.02	6.1
0-22	10	18	0.509	0.03	4.1
0-24	10	24	0.679	0.04	4.7
0-58	50	10	1.414	0.05	7.0
12-42	15	24	1.018	0.03	4.8
20-37	10	18	0.508	0.02	5.8
17-51	30	11	0.933	0.02	7.1
13-68	25	15	1.555	0.02	7.3
19-78	45	22	1.908	0.17	9.0
48-65	15	32	1.357	0.04	6.2
30-58	10	55	1.555	0.02	4.8

Conclusions

The paper presents a possible method for studying heavy traffic in large cities. The paper offers an estimate of both the downtime of the car and the speed of the exhaust gases. The exhaust gas velocity is proportional to the exhaust gas volume. The conducted research provides an opportunity to assess the level of congestion and the corresponding environmental consequences of them specific to urban areas.

1. In this study, the dimensionless coefficient, K_{stop}, is introduced, which is the ratio of the time at which the car is at rest (speed below 1 km·h^{-1}) to the total time for passing the relevant section. This indicator proves to be sensitive enough. The coefficient reaches the road sections loaded in certain time zones to values 0.4 - 0.45. The use of this coefficient gives more accurate results compared to the average speed for estimating the load in specific sections in large cities.
2. To study the amount of emissions in the congested sections of urban traffic, the indicator of the volume of exhaust gases $W_{ex.gas}$ has been introduced. This indicator is important for estimating the total amount of exhaust gases. It can be used to calculate the total volume of exhaust gases for the surveyed urban area. This volume is directly related to the increase in atmospheric temperature during heavy traffic. This effect has not been studied in this paper.
3. The study with the proposed results shows that the use of validated cycles (WLTP) cannot be an accurate indicator of vehicle traffic in urban conditions and in the presence of bottlenecks in traffic.
4. Estimating traffic congestion in large cities using an average speed is too general and does not provide a realistic estimate for the busiest sections. It is true for areas with medium load, where the downtime is minimal (less than 10%). The use of downtime or downtime ratio to assess the busiest road sections allows decisions to be made related to changes in flow management.

5. The traffic in the considered road sections is non-stationary for internal combustion engines. Measurement of the amount of harmful emissions is important for the speed of the exhaust gases. To reach a certain speed in a shorter time (driving with higher accelerations) creates conditions for higher average speeds of exhaust gases. This also leads to greater pollution.

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Author contributions

Conceptualization, L.K., E.S. and E.D.; methodology, L.K., E.S. and E.D.; validation, L.K and E.S.; formal analysis, L.K., E.S. and E.D.; investigation, L.K., E.S. and E.D.; data curation, L.K., E.S. and E.D.; writing – original draft preparation, L.K., E.S. and E.D.; writing – review and editing, L.K., E.S. and E.D.; visualization, L.K., E.S. and E.D. All authors have read and agreed to the published version of the manuscript.

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