

Article

Provision of System for Internalization of Damage from Actual Emissions of Pollutants by Vehicles in Urban Areas

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Abstract

Urban sustainability is tied to transport sustainability. Limitations of tools for internalization of externalities and distortions of incentives for environmentally friendly behavior of vehicle owners hinder the transition to sustainable urban development. The complexity of accurately assessing pollutants emissions by motor vehicles makes it difficult to internalize the economic damage caused by actual emissions. The purpose of the study is to develop a system for organizing the internalization of damage caused by actual emissions of pollutants by motor vehicles in the territory. For motor vehicles, the power consumption depends on operating conditions and driving style. Effective power affects the volume of exhaust gases, and the quality of the power unit and the efficiency of its management affect the content of pollutants in the exhaust gases. A system of interaction of environmental policy instruments is proposed, which allows for the internalization of economic damage from actual emissions of pollutants from vehicles. The basis of the system is dependencies of the masses of pollutant emissions with vehicle exhaust gases on the actual engine power used. The system assumes the internalization of damage from emissions, joint use of the mechanism of buying and selling rights to pollute the environment (for public and freight transport), and emission payments (for other types of vehicles). The system for accounting for actual emissions will improve the adequacy of comparing alternatives for the movement of passengers and goods, including with electric transport and unmanned systems. The system for ensuring the internalization of damage from actual emissions will reduce distortions and create adequate incentives to reduce damage from emissions.

Keywords: internalization of external effects; environmental policy instruments; actual emissions of pollutants by motor vehicles; direct and indirect methods of assessing the toxicity of exhaust gases



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1. Introduction

In the modern world, one of the main sources of environmental pollution is motor transport [1–3]. This situation is especially acute in large metropolitan areas [4]. Many countries already have a variety of systems in place to internalize externalities from vehicle emissions [5–10]. The policy instruments for reducing externalities from the impact of motor transport include command-and-control and incentive policies. The positive effect of command-and-control and incentive policies is demonstrated by the examples of the emission and fuel standards introduced in the USA and the driving and parking restrictions introduced in Singapore. Incentive policy methods are considered the most effective in terms of public perception. Effective modern instruments include: subsidies for the disposal

of old vehicles; subsidies for the purchase of more fuel-efficient vehicles [11,12]; ban on the purchase of fossil fuel vehicles [13]; benefits for using toll road sections; and the sale of unused credits [14].

The following can also be identified as tools for reducing external costs from air pollution by motor vehicles: a model for introducing taxes on gasoline and diesel fuel (in European countries—this type of tax accounts for half of the net price of fuel [7,9,10]; carbon taxation [5]; improving fuel quality to reduce pollutant emissions [15]; pay-as-you-go insurance or peak congestion rules [7]; the introduction of distance-based pricing or per-mile premiums for auto insurance policies [16]; and the use of transportation pricing policies [6]. Norway's positive experience with introducing a tax on the ownership and use of motor vehicles effectively covers external costs associated not only with pollution but also with road traffic injuries [6], although this was not the primary objective [16]. Another example of the internalization of externalities is the approach of corrective taxes on vehicles with high levels of pollution and the introduction of reduced tax rates for the use of vehicles with a higher level of environmental friendliness [17]. A number of external costs of road transport, such as congestion, noise, air pollution, insurance claims, are considered expenses that are not included and not paid for in transport prices [18]. Voluntary insurance [19] or emission taxes [20] can be applied to them.

Experience from different countries suggests different methods of road pricing that help reduce air pollution in big cities and, importantly, can lead to a reduction in traffic congestion [4]. One of the alternatives to this is the transition to complex underground toll highways [21]. The positive experience of introducing congestion pricing has been applied in London, and in the USA, there is a system of toll road lanes that have a high occupancy rate [11]. Based on the analysis of data from the city of Santiago, Chile, it is proposed to apply a Pigouvian tax and subsidize the use of public transport to effectively manage the externalities of motor transport [8]. In Taipei, Taiwan, an analysis of road pricing shows that by imposing a Pigouvian tax on the accident externality, the tax collection will be higher than that on the mixed-vehicle congestion externality [22]. Despite the attractiveness of the Pigouvian tax in the fight against congestion, there may be an acute adverse reaction of the population to the authorities and an obvious inequality of users in the focus of "poor" and "rich" [14].

The eco-compensation method is used in Zhejiang Province, China. It is based on a flexible system of payments for ecosystem services and effective public administration [23,24]. Based on data from Japan, it is recommended to use a three-stage tax: on purchase; on ownership; and on the class of the vehicle used, its service life, the owner's driving technique and other factors of operation. According to the authors, the introduction of the tax will significantly reduce CO₂ emissions from motor vehicles [24]. The transfer of external costs to private transport encourages the population to switch to using public transport. However, the introduction of a tax regime will primarily affect certain segments of the population with low incomes [25]. Theoretical aspects of the internalization of externalities from road transport using an economic engineering method, considered on the example of Tunisia, allowed for a quantitative assessment of congestion and pollution levels from road transport [26]. A study of the external and internal costs of private and public transport using data from the city of Auckland, New Zealand, found that the total revenues collected did not cover even 50% of the total transport costs [27]. Despite the so-called transport poverty [28], the poor should not go unpunished when directly involved in polluting the environment. It is also worth noting that an underestimated benefit to society is the directive punishment of current "free riders" [29].

Effective urban transport planning can significantly reduce environmental pollution and damage to human life and health. A vehicle quota system is used in Beijing [30], while Singapore uses a vehicle quota system for auctions to allocate title certificates [31].

The carbon emission trading system for China's road freight transport [32] is a comprehensive policy framework developed specifically for China's road freight sector. The approach is aimed at reducing CO₂ emissions, and it is based on the average values of specific CO₂ emissions. The mass of emissions is determined taking into account the type of fuel, the age of the transport, the grouping of freight transport by weight and kilometers traveled. This number of factors looks like a compromise between increasing the accuracy of emissions estimates and minimizing administrative costs. The model provides additional incentives for updating the fleet of vehicles on the territory. At the same time, the operating model of a particular vehicle can increase the incompleteness of fuel combustion and stimulate an increase in emissions of other pollutants that are more dangerous to the population, ecosystems, physical objects, including from the point of view of the climate agenda. The range of possible values of the mass emissions of pollutants, depending on the behavior on the road, can be significant [33]. To calculate the CO₂ emissions, the full load and maximum mass of the vehicle are considered. The use of the maximum mass of transport and the lack of differentiation in terms of cargo weight reduces the number of alternatives to optimize the environmental integrity of the behavior of owners and users of vehicles. Indirectly, the model creates incentives for maximum loading and overloading of transport, the transportation of heavier goods in general, and for inflating prices for the transportation of goods with a lower mass. For the task of creating incentives to reduce CO₂ emissions by freight transport, the approach proposed in this paper has good prospects. However, for large cities, it is important to take into account other more dangerous pollutants contained in the exhaust gases of vehicles. In addition, limitations of the vehicle emissions assessment approach, the underlying internalization tool, and policy shortcomings may make it difficult and distorting to compare alternatives to trucking by different modes of transport [34]. The general consequences of vehicle operation are also an important element in comparing alternatives. Various authors note the problems of accounting for external environmental costs associated with transportation [18,32,33,35–37]. The use of a single emission limit in externality internalization tools limits their flexibility and effectiveness [35].

Some authors try to circumvent the problem of assessing the external effects of motor transport by assessing the willingness to pay and the acceptability of policy instruments for the population of the territory, as well as analyzing various factors and measures to stimulate public support for internalization of externalities [38–41]. At the same time, in order to compare environmental alternatives and solve forecasting problems, it is necessary to assess the consequences of various decisions. As a result, ignoring the problems of assessing the externalities of motor transport can lead to distortions of models of environmentally sound behavior and significant opportunity costs (lost profits) at different levels of decision-making. The use of biased policy instruments and a favorable attitude of the population without an adequate assessment of the consequences can lead to a short-term environmental result. However, over time, the revealed unfairness in the distribution of costs related to the external effects of motor transport can be perceived by the population as specific forms of exploitation and reduce confidence in politics and bureaucracy [42].

The tools considered and mainly promoted are related to the internalization of indirectly determined damage from vehicle emissions or payment for environmental quality acceptable to the population of the territory. Approaches to internalization of economic damage from actual emissions for vehicle transport are not considered. This is also related to information limitations. When choosing and justifying internalization instruments,

researchers face the problem of the reliability of assessing emissions from vehicles and the transport system of the territory as a whole under conditions of information limitations, such as operational characteristics.

Considering the common methods of assessing emissions from motor vehicles for the formation of an accounting system, we note the following: assessing emissions from motor vehicles using a portable emissions measurement system [43]; a system dynamics approach to the vehicle life cycle [44]; binning method—operating mode of the vehicle emission simulator [45]; correlation analysis [46] and others.

To assess the pollution of megacities, the method of dynamic road network simulator is used. It models the choice of mode, start time and route of motor vehicles. The calculation of the toll, which is expected to effectively reduce emissions from motor vehicles and reduce traffic congestion, is based on the data obtained. When applying toll calculations for motor vehicles, such factors as speed and wind direction, travel distance, location in a traffic jam and relative to residential buildings should be taken into account [4]. The useful life of a vehicle plays an important role, as there is a direct relationship between the increase in useful life and the impact on the environment. Using the portable measurement system, Abualqumboz et al. [47] found that ammonia emissions from older gasoline vehicles were higher than those from newer vehicles. This is partly due to the fact that new vehicles were equipped with new three-way catalytic converters. The maximum useful life of a vehicle with minimal financial costs for the consumer and minimal environmental pollution is 18 years [48].

The vehicle emissions monitoring system using an artificial neural network analyzes engine speed, rotation frequency, torque, coolant temperature, fuel/air ratio, and intake air mass flow. The accuracy of the obtained results of the pollution level forecast directly depended on the number of the listed parameters considered simultaneously. The artificial neural network was trained using real driving data measured using a portable emissions measurement system and an on-board diagnostics data recorder [49]. Multi-species neural network is used to predict fuel consumption of motor vehicles [50], and as a result, based on the data obtained, it is possible to make a forecast of the level of exhaust emissions.

A system for accounting for vehicle emissions using agent-based modeling has proven ineffective. The modeling results were far from the real data obtained using a portable emissions measuring device [51]. A method for forecasting medium- and long-term vehicle emissions based on global and local spatiotemporal graph network captures changes in vehicle emission information and forecasts medium- and long-term time series [52]. In different territories, the emission coefficients from motor vehicles may differ due to the characteristics of traffic flow, road network, type of driving and number of vehicles [53]. Xu et al., in a study of the level of PM_{2.5} fine particles in the air, concluded that the higher the level of economic growth in the provinces, the higher the level of PM_{2.5} pollution [54]. Limitations of models for estimating vehicle pollutants emissions in internalizing externalities contribute to the development of short-term scenarios for urban transport policy [37] instead of dynamic models for optimal management decision-making.

When considering the stage of economic assessment of the consequences of air pollution, researchers often use limit values [6–8]. Less frequently, researchers consider the annual risk for the population and the statistical value of life [55–58], negative consequences of emissions for man-made and natural objects [59–62]. It is also worth considering the direct external costs for the population, associated, for example, with road accidents [16].

Reducing the external effects of motor transport in the territories in the context of increasing the sustainability of road freight transportation allows us to identify three categories of measures: based on policy and regulation, innovative technologies, logistics and transport efficiency [63]. Within each of these areas, and in general, in order to make

the most effective decisions and compare alternatives, an adequate assessment of the external effects of motor transport is necessary. Limitations of the assessment approach and complexity [36] have a significant impact on the decision-making process and political consequences.

Regulating and controlling the time and place of movement of different categories of vehicles is an effective measure to combat air pollution [64]. To reduce toxic emissions from motor vehicles various filters [65–67] and catalysts [68–70] can be used. A modeled method of using gasoline blended with ethanol showed a reduction in PM_{2.5} concentrations by an average of 9% and O₃ by 2.5% [71]. One of the main methods for reducing emissions from the motor transport complex in local areas is the transition to electric traction and an increase in the share of electric transport in the area [72–74]. The transition to new energy vehicles (EVs) is widely supported by environmentally concerned populations in China [74]. In Hainan Province, China, the authorities are the first in the world to ban the sale of fossil fuel vehicles by 2030. The studies predict a reduction in pollutant emissions (NO_x, CO, VOCs, PM_{2.5}, PM₁₀) into the atmosphere, but at the same time, CO₂ emissions are predicted to increase due to the increase in new energy vehicles compared to the existing vehicle fleet [13]. Autonomous electric vehicles have an advantage over other types of vehicles and reduce greenhouse gas emissions by up to 34% [5]. Automating urban vehicles will significantly reduce external effects [75]. Based on US data, it is projected that the transition to electric vehicles with improved battery technology will reduce pollutant emissions by up to 54% by 2050 compared to 2020 pollution levels [9]. Such a transition would also help reduce fossil fuel consumption and battery replacement costs [76]. Current emission calculation standards do not take into account the impact of modern electric transport on environmental pollution, which is unacceptable [77]. At the same time, in the long term, the transition to electric vehicles should allow for a significant reduction in pollution levels [72,73]. The system of regulating vehicle emissions currently in force in European countries has proven to be insufficiently effective and requires new legislative revisions. Among other things, a balance is needed between the operation of zero-emission vehicles and the economic sustainability of the automotive industry [78].

An analysis of the methods for calculating emissions of pollutants from motor vehicles has made it possible to identify a number of incorrect provisions that prevent an adequate reflection of the actual emissions of exhaust gas components in the territory. The general disadvantages of the methods can be considered [79]: the calculation of pollutant emissions using the average operating fuel consumption, i.e., approximately; ignoring the features of engine operation in modes; an incomplete accounting for emissions of aerosol lead compounds; the lack of accounting for soot emissions from gasoline engines, which are the main “suppliers” of solid components of exhaust gases into the atmosphere of cities; an approximate calculation of the mass of pollutant emissions, based on an arbitrary choice of the transmission gear ratio, depending on which the average specific emission indicators are determined; hiding in empirical expressions with assigned coefficients logic for calculating emissions of pollutants when performing transport work by a vehicle.

The tools considered have their advantages and limitations. In the context of the topic of this study, we have presented a summary of the limitations of the main approaches considered in Table 1.

Researchers are trying to balance the characteristics of the models to achieve their goals optimally. Improving some characteristics of the internalization system of externalities can negatively affect others. The search for compromises of goals and opportunities when building an internalization system ultimately boils down to compensating for some characteristics at the expense of others and reducing the adequacy of such a system to its goals. Ignoring, in combination or separately, such characteristics as administration, accuracy

of assessment, flexibility for participants, incentives for technology and environmentally sound behavior, the ability to compare alternatives at different decision-making levels, accuracy in determining the location of emissions, the ability to promptly report emission data for stakeholders, the number of pollutants taken into account, and the need for adaptation for other regions can significantly reduce the effectiveness of the internalization system of the externalities of motor transport.

Table 1. Limitations of the considered approaches for assessing and internalizing the externalities of motor transport.

Source	Topic	The Method of Estimating the Mass of Pollutant Emissions by Motor Vehicles, Its Features	Limitations
[11]	Part I: Externalities and Economic Policies in Road Transport (review)	Not considered	An incentive policy requires accurate data on marginal external costs, which are difficult to implement if the information is incomplete.
[12]	Can New Energy Vehicles Subsidy Curb the Urban Air Pollution? Empirical Evidence from Pilot Cities in China.	Panel data analysis, evaluation based on a fixed effect. Fixed effect score.	The use of electricity produced primarily from coal can offset the environmental benefits of new energy vehicles source (NEVs). Comparison without detailing the possible mass emissions of pollutants from vehicles, the range of values of which may be significant. The accuracy of the estimate is conditional. The difficulties of comparing alternatives.
[13]	How Does Vehicle Emission Control Policy Affect Air Pollution Emissions? Evidence from Hainan Province, China	Using the GAINS IV Asia model for integrated assessment. Estimation based on specific emissions of pollutants per unit mileage. Additional factors: • Engine specifications; • Efficiency of emission control systems (e.g., catalytic converters, particle filters); • Fuel quality and its compliance with standards; • Operating conditions (urban or suburban trips, traffic jams, etc.).	Emission coefficients and cost parameters for emission control technologies are developed within the model based on the literature and consultations with stakeholders. This can both help to clarify the specific emissions in the territory, and distort them under pressure from stakeholders. Adaptation is needed for different territories. The accuracy of the estimate depends on the accuracy of the data. It may be difficult to compare alternatives. There is limited flexibility for participants. Low accuracy in determining the location of emissions.
[14]	Managing Bottleneck Congestion with Tradable Credit Scheme under Demand Uncertainty	The Monte Carlo method. There is no estimate of emissions.	An incentive policy requires accurate data on marginal external costs, which are difficult to implement if the information is incomplete.
[7]	Road Fuel Taxes in Europe: Do They Internalize Road Transport Externalities?	Estimation of the mass of pollutant emissions depending on fuel consumption. Using emission data from the European Environment Agency and the International Energy Agency; Calculation of external costs based on models and data from EU-funded projects, as well as TREMOVE and Odyssee databases.	Fuel taxes are not an accurate enough tool to account for pollutants other than CO ₂ ; The difficulty of taking into account differences in costs between countries when developing universal tax mechanisms. Difficulties in comparing alternatives. There is limited flexibility for participants. Low accuracy in determining the location of emissions. It is more of a fiscal function.

Table 1. Cont.

Source	Topic	The Method of Estimating the Mass of Pollutant Emissions by Motor Vehicles, Its Features	Limitations
[9]	Quantifying Policy Gaps for Achieving the Net-Zero GHG Emissions Target in the U.S. Light-Duty Vehicle Market through Electrification	VISION model (for forecasting vehicle fleet and greenhouse gas emissions); Estimation based on specific emissions of pollutants per unit mileage. Additional factors: • Speed of movement; • Operating conditions (city/highway); • Age of the vehicle; • Fuel quality. The forecast of annual mileage per vehicle was carried out taking into account economic factors (GDP, household income), fuel prices, public transport development, and urbanization.	Difficulties in comparing alternatives. There is limited flexibility for participants. The average accuracy of determining the location of emissions. The accuracy of the estimate depends on the accuracy of the data. The need to adapt for other regions.
[10]	Fuel Consumption Dynamics in Europe: Tax Reform Implications for Air Pollution and Carbon Emissions.	Analysis of panel data on 16 European countries for 1990–2012.	Previous studies have not fully taken into account the transition to diesel and the endogeneity of fuel prices; The difficulty of estimating the dynamics of fuel consumption changes over time. Difficulties in comparing alternatives. There is limited flexibility for participants. Low accuracy in determining the location of emissions. It is more of a fiscal function. There is no way for stakeholders to promptly report emission data. The stimulation of technology is limited.
[5]	Autonomous Electric Vehicles Can Reduce Carbon Emissions and Air Pollution in Cities	For internal combustion engines, the estimate is based on specific emissions of pollutants per unit of fuel consumption. For autonomous electric vehicles, the estimate is based on energy consumption and the carbon footprint of the network. Additional factors: consideration of acceleration, braking, and road slope.	Potential increases in travel demand with the introduction of autonomous vehicles may reduce the environmental impact.; The influence of the source of electricity generation on the environmental efficiency of electric vehicles; Estimating pollutant emissions from fuel consumption may not take into account some behavioral or macroeconomic factors. Only CO₂ and NO_x emissions are taken into account
[23]	The Effectiveness of Eco-Compensation in Environmental Protection -A Hybrid of the Government and Market	Synthetic Control Method. Data analysis from various sources.	High transaction costs and imperfect payment mechanisms for ecosystem services
[26]	Internalization of External Congestion and CO ₂ emissions Costs Related to Road Transport: The Case of Tunisia	Estimation based on specific pollutant emissions per unit of fuel consumption.	Estimation of CO₂ emissions only. Difficulties in comparing alternatives. Low accuracy in determining the location of emissions. The accuracy of the estimate depends on the accuracy of the data.

Table 1. Cont.

Source	Topic	The Method of Estimating the Mass of Pollutant Emissions by Motor Vehicles, Its Features	Limitations
[30]	Transport Decarbonization in Big Cities: An Integrated Environmental Co-Benefit Analysis of Vehicles Purchases Quota-Limit and New Energy Vehicles Promotion Policy in Beijing.	The MAPLE model (Multi-pollutant Abatement Planning and Long-term benefit Evaluation) Estimation based on specific emissions of pollutants per unit mileage. Additional factors: • Operating conditions (urban, rural roads, highways) and climatic factors; • Emission control technology; • “Hot” and “cold” (when warming up) engine operation modes.	Difficulties in comparing alternatives. The accuracy of the estimate depends on the accuracy of the data. The need to adapt for other regions. There is limited flexibility for participants. The average accuracy of determining the location of emissions. There is no way for stakeholders to promptly report emission data.
[32]	Carbon Emission Trading System for China’s Road Freight Transport: Considering Reward and Punishment Ladders	Estimation based on average specific CO₂ emissions per unit of fuel consumption. The mass of emissions is determined taking into account the type of fuel, the age of the transport, the grouping of freight transport by weight and kilometers traveled. To calculate the CO₂ emissions, the full load and maximum weight of the vehicle are considered.	Accounting for CO₂ emissions only. Difficulties in comparing alternatives. The average accuracy of determining the location of emissions. Incentives for updating the fleet of vehicles on the territory. It requires the creation and maintenance of a control system. The accuracy of the estimate depends on the accuracy of the data.
[38]	Acceptability of a Mobility Pricing Scheme: Reducing Externalities in Urban Transportation.	The study uses data from local, national, and international sources, as well as peer-reviewed publications, to assess the external costs of various types of mobility.	An incentive policy requires accurate data on marginal external costs, which are difficult to implement if the information is incomplete.
[4]	Pricing Vehicle Emissions and Congestion Externalities Using a Dynamic Traffic Network Simulator	Using the dynamic simulator of METROPOLIS transport networks. Estimation based on specific emissions of pollutants per unit mileage. Additional factors: • Speed of movement; • Engine operating modes; • Ambient temperatures; • The age of the vehicle.	Difficulties in comparing alternatives. The accuracy of the estimate depends on the accuracy of the data. The need to adapt for other regions. There is limited flexibility for participants. The average accuracy of determining the location of emissions. There is no way for stakeholders to promptly report emission data.
[37]	Ending the Myth of Mobility at Zero Costs: An External Cost Analysis.	Estimation based on specific emissions of pollutants per unit mileage. Data on emission factors are used from the HBEFA handbook and the TREMOD tool.	The methodology is mainly applicable to urban conditions; it is difficult to adapt it for other territories. The model is simplified and does not take into account the complexity of mobility-related solutions. The results are not suitable for detailed spatial and temporal studies.

In the reviewed scientific literature, the “free rider” problem remains insufficiently studied. Existing instruments for internalizing external effects from vehicle emissions ignore the actual damage caused by a specific vehicle and user. Indirect instruments for internalizing external effects from vehicle emissions can both underestimate and overestimate the actual damage for different vehicles in a territory. Depending on the operating time and driving style, the negative consequences of emissions from a single vehicle can vary significantly. An average model for assessing these characteristics for different types of vehicles can significantly distort user incentives and contribute to overexploitation of public resources (air, assimilation potential of the ecosystem (the ability of elements of the

natural environment (green spaces, soil, mineral rocks and inorganic residues, atmospheric moisture, and water of reservoirs) and man-made (artificial) objects neutralize and process harmful substances without changing their basic properties [80]), infrastructure, etc.).

There is a lack of attention paid to improving the accuracy of the assessment of vehicle emissions in the tools for the internalization of externalities. As far as we know, the problem of organizing the transition from indirect assessment of emissions to determining the actual emissions of pollutants by motor vehicles in the context of the internalization of externalities has not been addressed in scientific sources. We aim to fill this gap by focusing on the internalization of the damage caused by actual vehicle emissions. By improving the accuracy of the assessment of each vehicle's contribution to environmental pollution and internalizing the damage caused by more accurately measured emissions, we can enhance incentives and provide more options for environmentally conscious behavior.

Vehicle emissions of pollutants are influenced by many factors at the regional and local levels. Information constraints and distortions reduce the effectiveness of decisions made at various levels of management. The development and implementation of a vehicle emission accounting system will improve the effectiveness of management decisions in general and internalize externalities from vehicle emissions in the territory. The use of direct methods for internalizing damage from vehicle emissions is hampered by problems of assessing and accounting for actual emissions from individual vehicles in a territory in real time. Addressing these issues will help create effective incentives to reduce emissions from specific vehicles and users.

Indirect environmental taxes and environmental charges based on the indirect assessment of emissions and negative consequences from vehicles on the territory can distort incentives for increasing the environmental integrity of the behavior of participants in environmental pollution by motor vehicles. Information restrictions on pollutant emissions by cars hinder the use of emission payments. The purpose of the study is to develop a system for organizing and ensuring the internalization of damage from actual pollutant emissions by vehicles on the territory.

To increase the quality of incentives, it is necessary to improve the quality of information support and internalize economic damage from actual environmental pollution by motor vehicles. Reducing information restrictions on the impact of vehicles on environmental quality will improve the efficiency of the stimulating function of environmental policy instruments.

The article proposes a system for internalizing economic damage from actual emissions of pollutants by vehicles using mathematical models for calculating the mass of pollutant emissions by vehicles into the atmosphere (based on experimentally determined dependencies of pollutant concentrations in exhaust gases on the engine load characteristics of each vehicle through vehicle emission testing (VET)) and the joint functioning of emission payments with the mechanism for buying and selling rights to pollute the environment.

2. Materials and Methods

2.1. Method for Assessing Pollutant Emissions from Motor Vehicles to Form an Accounting System on the Territory

The solution to the issue of estimating pollutant emissions from motor vehicles relies on a mathematical model of air pollution from mobile sources. This model can be used to monitor and control the quality of air in cities by adjusting traffic flow characteristics in real-time. The masses of pollutant emissions into the air by vehicles are determined in the following sequence [3]:

1. The effective engine power is calculated for vehicle operating modes depending on the driving parameters (the average vehicle speed is taken as the main kinematic characteristic; the acceleration of the mobile source is also used for a more accurate analysis);
2. The volumetric flow rate of exhaust gases is calculated as a function of the effective engine power and the associated excess air coefficient, parameters dependent on the composition of the fuel, combustible mixture, and characteristics of the piston–cylinder group;
3. The concentration of microimpurities in the combustion products of the mixture is determined depending on the effective engine power or excess air coefficient;
4. The mass flow rate of pollutants is found as the product of the volumetric flow rate of exhaust gases and the concentration of microimpurities.

Further, the process of air pollution by pollutant emissions on the street road network is considered, taking into account the following conditions: firstly, the average speed of the traffic flow is represented by the average speed of vehicles by purpose (passenger cars, trucks, minibusses, buses, etc.) and depends on the number of vehicles located on the road section; and secondly, the composition of the traffic flow and the time of engine operation of the vehicle in modes (idle, acceleration, constant speed, braking) are taken into account. The consistent addition and complication of the model, based on the detailing of the process of movement of motor vehicles, does not increase the accuracy of calculating the emissions of toxic and carcinogenic substances with the products of vehicle emissions so much, but is a relatively objective reflection of the process of air pollution by vehicle emissions. The scheme for assessing the mass of pollutants emitted by a vehicle as a function of engine load is shown in Figure 1.

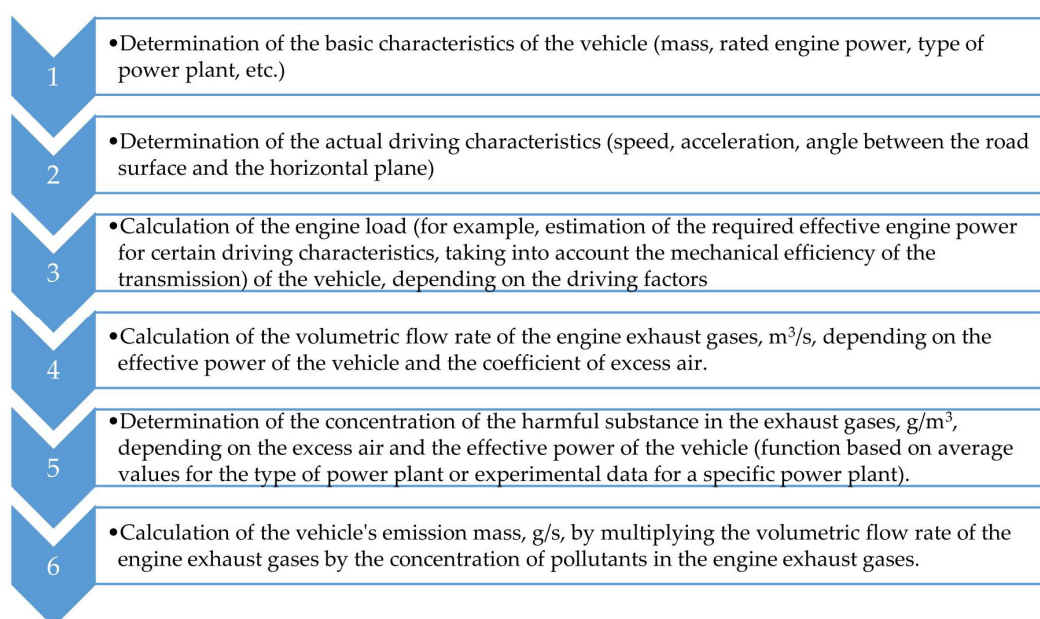


Figure 1. Assessing the mass of pollutants emitted by a vehicle as a function of engine load.

The analysis of the mathematical model allows us to note that the most significant error in the calculation of pollutant emission masses is often introduced by the dependence of pollutant concentrations in exhaust gases on engine loads, which often differ in nature and values. Any correct theoretical data on the content of toxicants in emission products that are worthy of attention are usually based on significant arrays of experimental information. At the same time, the accuracy of the calculation depends most of all on the technical parameters of a specific engine, the terms and conditions of its operation. The content of

microimpurities in combustion emissions varies significantly depending on the engine brand, and the maximum ranges of their change before and after major repairs vary widely [79].

To solve the problem of dynamic assessment and the formation of a system for accounting for actual emissions of pollutants by vehicles, the method of assessment based on the effective engine power will be used [3,81]. Within the framework of this approach, the mass of pollutant emissions by motor vehicles is a function of the effective power $Mp = f(Ne)$. In addition, losses during vehicle operation are taken into account. At the same time, the volume of exhaust gases directly depends on this indicator of vehicle operation, taking into account the transmission efficiency. The concentration of pollutants in the exhaust gases is a qualitative characteristic of the energy generation process. This function, having a similar form for one pollutant and type of fuel, can have different values depending on the characteristics of a particular vehicle and its operating conditions.

The choice of the method for assessing emissions from vehicles is due to the possibility of its use for dynamic assessment of actual emissions of pollutants by specific vehicles. The assessment approach used is also distinguished by such characteristics as simplicity, transparency for the formation of incentives for environmentally friendly behavior, and the possibility of using elements of built-in equipment on modern vehicles. The characteristics of the vehicle and its operation required for assessing emissions within the framework of this method will be used to form a system for accounting for emissions from motor vehicles. Based on the emission accounting system and the systemic approach, environmental policy instruments will be considered for internalizing economic damage from actual emissions of pollutants by vehicles on the territory.

2.2. Data for Modeling the Mass of Pollutants Emitted by a Single Vehicle on a Road Network Section

The initial data for modeling the mass of pollutants emitted by a single vehicle was obtained based on the results of the study [82] and can be represented by the following main characteristics:

1. The calculations are performed for a road network section with a length of 185.6 m, urban conditions, and a minimum slope between the road surface and the horizontal plane.
2. The object of the study is a passenger car with a gasoline engine, a total mass of 1500 kg and a rated power of 69,250 W.
3. The estimated period and year of manufacture of the vehicle are 2008.
4. The average speed of the passenger car on the considered section is 10 m/s.
5. The fractions of engine operation time in different modes are presented in Table 2.

Table 2. Fractions of the engine operating time in modes.

Alternative Vehicle Motion Characteristics	Idling	Acceleration	Constant Speed	Braking
Alternative 1	0.12	0.37	0.22	0.29
Alternative 2	0.17	0.32	0.22	0.29
Alternative 3	0.17	0.27	0.22	0.34
Alternative 4	0.17	0.27	0.27	0.29
Alternative 5	0.27	0.27	0.22	0.24

2.3. Reducing the Negative Impact of Motor Transport on the Environment Using Environmental Policy Instruments

A far-sighted environmental policy is based on detailed and sufficiently complete information about the existing natural potential, the maximum allowable load on the ecosystem, and the anthropogenic impact on the environment and humans [42,82].

Analysis of literary sources [5,7–11,24,44,63,82–88] allowed to identify a set of environmental policy instruments that have prospects or are already used in world practice to reduce the negative impact of motor vehicles on the environment. We will consider the features of using environmental policy instruments to reduce the “pressure” of vehicle pollutant emissions on the environment.

Administrative and control instruments of environmental management can be used to directly influence the environmental performance of both legal entities and individuals in the production and operation of automobiles. The fundamental instruments of this group include environmental and natural resource legislation, the system of standards and regulations applied to environmental protection and the rational use of natural resources, as well as environmental and resource target programs. These environmental policy instruments are used to formulate a strategy for the transition to sustainable development in a territory or to solve specific environmental problems: goals are outlined (an acceptable level of impact of pollutants on the environment; the desired quality, for example, of atmospheric air), and conditions for achieving them are ensured through a regulated legal framework (legislative consolidation of the functioning of specific environmental policy instruments, implementation of certain environmental and control procedures, etc.). A systemic solution to specific problems, such as reducing vehicle emissions, improving the quality of atmospheric air in a city, etc., get achieved through a comprehensive target environmental program, which may include environmental policy instruments of different groups. Ultimately, overcoming the difficulties of reducing the negative impact of motor transport on the environment involves going through the presented key stages of forming an environmental strategy and choosing the optimal system of environmental policy instruments for its implementation.

Direct control can be carried out at the operational level of planning and management of the instruments of this group. During environmental assessment, projects (intentions) are analyzed, during environmental audit—actually functioning objects (entities of economic activity), and for environmental certification, the object of analysis is the quality of products, services, work, etc.

The simplicity and directness of the means in achieving the required level of environmental quality, as well as the convenience of control by environmental management bodies, can be attributed to the advantages of administrative and control instruments of environmental policy [11,63,82,83,86,88]. Disadvantages are determined by weak effectiveness in terms of stimulating innovation and achieving higher environmental performance characteristics than prescribed by environmental requirements; environmental policy instruments of this group can hinder the ability to respond flexibly to various situations.

The purpose of using economic instruments is to change the behavior of entities that have a negative environmental impact by transferring external costs of destruction or depletion of the environment to the category of internal ones and changing the set and structure of incentives available to these entities. The use of instruments of this group to reduce the negative impact of motor transport will allow us, firstly, to stimulate environmentally friendly behavior of economic entities and, secondly, to obtain resources to finance measures to improve the quality of the environment. The choice in favor of using certain policy regulation instruments should be made by taking into account the criteria for effective control over compliance with established rules and procedures [82,83,89].

The implementation of the “polluter pays” principle in practice can be carried out through environmental charges or taxes. The main advantage of environmental taxation is that it can change consumer behavior and have a strong motivating effect on pollutants [90–94]. One of the difficulties is that, since taxes represent revenue for the budget,

there is no guaranteed connection between the use of budget funds and improved environmental protection [90,91].

In different countries, attempts are being made to reduce the negative impact of vehicle exhaust gases on the environment through various fees and taxes [5,7,9–11,63,86,88]. Due to the institutional characteristics of the territories, blindly copying successful solutions may be less effective or lead to institutional traps. Due to the need to create special control and measuring equipment to determine the actual emissions of pollutants by vehicles and the economic damage they cause, the issue of using environmental charges is only at the stage of scientific discussions [79].

To reduce the negative impact of motor transport on the environment, it is important to use various forms and instruments of financing environmental protection measures [89]. In many countries, the tax system plays an important role in both financing and stimulating environmental protection measures. Various financial incentives can also be used as a form of financing environmental protection measures, the main purpose of which is to promote compliance with environmental regulations. An important tool is fees for non-compliance (fines and sanctions, for example, for exceeding the established emission limits). The limits of fees for non-compliance with standards should be set at a level sufficient to stimulate preventive approaches and measures to reduce emissions. The absence of financial sanctions for non-compliance with norms and standards may lead to pollutants ignoring the requirements of environmental legislation. Fines and sanctions require a very thorough system of monitoring and verification (their application may require high administrative costs). This significantly reduces the effectiveness of such economic instruments [82].

In order to overcome the existing gap between global leaders and local producers in the production of environmentally friendly products, it is necessary (in addition to tightening environmental requirements for products) to apply a different form of financial assistance to manufacturers of motor vehicles that create “conditions” for significant environmental pollution [42], which can be classified as various subsidies.

The advantages of economic instruments [11,63,82,83,86,88] can include the ability to develop sustainable incentives to reduce environmental pollution and scientific and technical innovations; the environmental policy instruments of this group enhance the flexibility of the environmental management mechanism, provide conditions for pollutants to independently determine their environmental protection strategy, and provide environmental protection with sources of financing. Disadvantages include the complexity of accurately setting the initial level of emission payments (including due to the lack of a strategic benchmark for acceptable environmental impact) and, caused by it, the uncertainty of the final environmental protection result; the need to constantly adjust the level of payments taking into account inflation processes; and the risk of reduced competitiveness of products due to high total environmental costs.

Due to the existing shortcomings of both administrative and control instruments and economic instruments, it is necessary to use new adequate management mechanisms. Given the limited resources (financial, administrative, etc.) and a critical attitude towards comprehensive state intervention in the environmental sphere, accompanied by numerous failures [95–97], “tools of moral and ethical influence and persuasion” can play an important role in reducing the negative impact of motor vehicles on the environment [82,83,86,88,98,99].

The considered instruments of environmental policy, having various advantages and disadvantages, are able to contribute to the reduction in economic damage from emissions of pollutants by motor vehicles to varying degrees. Of course, the search for the optimal set of instruments of environmental policy requires a systematic approach using performance

indicators, and the final choice will depend on the goals set and the influence of various factors. Taking into account the accumulated experience of the most environmentally friendly countries and the development of theoretical and analytical tools for substantiating management decisions will allow us to accumulate and more rationally distribute the resource potential of the territory. In modern conditions, an effective environmental policy is needed. Important tasks also lie in the field of mastering a new generation of environmental policy instruments. These include modern rules and instruments for implementing the environmental responsibility of entrepreneurship, the development of voluntary environmental agreements and the active use of the entire range of information instruments of environmental policy [86,87,99–101]. The necessary conditions for the application of these instruments are the development of institutions, the transition to information openness in the field of environmental protection, the transformation of the management style, etc.

However, for the effective use of various environmental policy instruments, it is necessary to overcome information limitations. In addition, to form sustainable incentives for environmentally responsible behavior, it is important to use economic instruments based on reliable information on pollutant emissions from motor vehicles.

3. Results

3.1. Theoretical Foundations of the System for Accounting for Actual Emissions of Pollutants by Motor Vehicles on the Territory

Accounting for actual emissions of pollutants by mobile sources involves periodic experimental studies of the characteristics of transport engines. In addition, testing makes it possible to analyze the adjustment of the vehicle's fuel equipment for the permissible content of microimpurities in exhaust gases depending on the changing engine power. Information on actual emissions of atmospheric pollutants can be recorded in the on-board computer's memory and sent to the territorial environmental data bank for subsequent processing. Within the framework of the practical implementation of the model of the process of pollutant emissions by motor vehicles into the air basin from the engine load, the main data necessary for the formation of the accounting system are:

1. The total number, composition and operating time of vehicles operating on the territory;
2. Operational characteristics of motor vehicles in the territory (speed, proportions of time spent by vehicle engines in certain modes, load parameters of engines with different ignition methods of the working mixture and mass–energy indicators);
3. The content of harmful substances in the exhaust gases of vehicles depending on the engine load.

The development of the accounting system from the point of view of increasing the reliability of the results of assessing actual emissions can be carried out in several stages.

The first stage can be implemented now with the support of state and municipal authorities for freight and public transport. These types of vehicles are subject to increased control by regulatory organizations and owners, which are often legal entities. Repeated routes and on-board computers reduce information restrictions on the conditions and characteristics of operation. For example, public transport in Russia is connected to control and tracking databases, including transport monitoring platforms based on a satellite navigation system [102]. Many major cities have similar information systems for public transportation [103,104]. Carriers of passengers and hazardous goods install satellite navigation equipment on vehicles and transmit data on traffic parameters to supervisory authorities in real time. Thus, the existing control systems and databases for such types of vehicles will provide the emission accounting system with adequate data, noted in points 1 and 2. With the help of reference information, it is possible to find the resistance

force to the movement of the vehicle, as well as the mass of the vehicle, the angle between the road surface and the horizontal plane, the rolling resistance coefficient, the nominal engine power and crankshaft speed, the maximum and minimum excess air coefficients, the moments of inertia of the rotating masses of the engine and vehicle wheels, and the rolling radius of the drive wheels.

The relative power of the vehicle engine (taking into account the mechanical efficiency of the transmission and the coefficient of accounting for rotating masses), the excess air coefficient and the crankshaft speed, as well as the mass flow rate of pollutants (taking into account the average values for different types of vehicles of the theoretical and empirical dependencies of the concentration of microimpurities in emission products on the relative power of the vehicle engine and the excess air coefficient, as well as the calculated effective efficiency of the engine), are determined analytically.

The second stage involves preliminary stationary experimental studies of pollutant concentrations in exhaust gases as functions of relative engine power and excess air coefficient in accordance with paragraph 3. Otherwise, the sequence of actions of the previous stage is preserved. Determination of empirical dependencies of pollutant content in exhaust gases on engine load can be transferred to car manufacturers or carried out as follows. The car is tested on special stands (drum or roller, and rotary), allowing us to measure the engine power of the car and the rotation frequency of the crankshaft. Simulation equipment makes it possible to create a load on the vehicle close to real conditions, and simultaneously, with special devices (gas analyzers, smoke meters, etc.), to record the concentration of harmful impurities in exhaust emissions. Torsion bridges and dynamometers are used to determine the traction force and torque developed by a mobile source.

The third stage already provides the continuous measurement of speed, acceleration, effective torque, power, crankshaft speed and effective engine efficiency of all types of vehicles by using portable mobile devices directly during movement, storing data in the on-board computer memory and transferring it to a single database. The concentration of microimpurities in the combustion products of the mixture is determined in the same way as in the second stage. Taking into account the obtained characteristics, the computer program calculates the values of the relative excess air coefficient, mechanical efficiency of the transmission, volumetric exhaust gases and the mass of emissions of atmospheric pollutants.

The fourth stage is accounting for actual emissions of pollutants by sensors installed on each vehicle.

3.2. The Modeling of Pollutant Emissions Masses by a Single Vehicle on a Road Network Section

To illustrate the importance of the proposed emission accounting system and the selected engine load criterion for forming a system for internalizing damage from pollutant emissions by vehicles on the territory, we will consider the results of modeling pollutant emissions by a single vehicle on a road section. As noted in Section 2.2, the time of passing a road section is constant for all considered alternatives, i.e., the average speed for all alternatives is the same and is 10 m/s. The alternatives differ in the structure of time spent in the following modes: idling, acceleration, constant speed, and braking (Table 2). The results of modeling of pollutant emissions for the alternatives from Table 2 are presented in Figures 2–4.

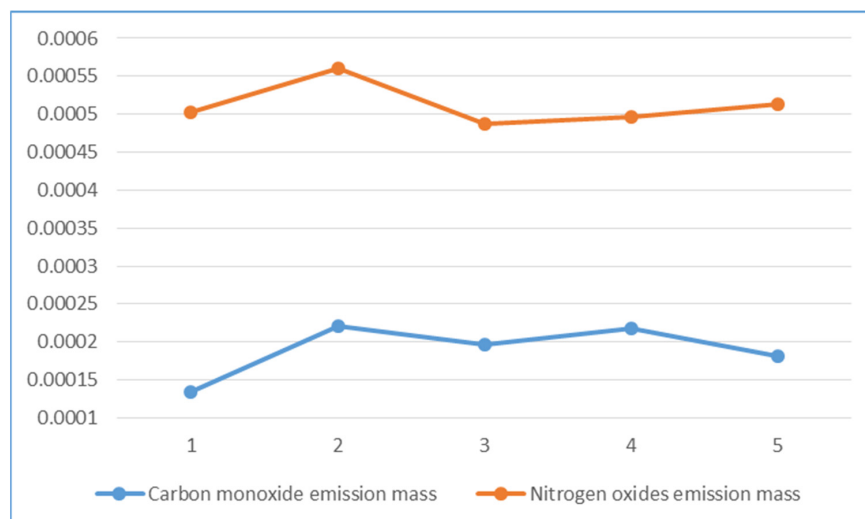


Figure 2. Masses of carbon monoxide and nitrogen oxide emissions on a road section from a single vehicle for several alternatives, kg.

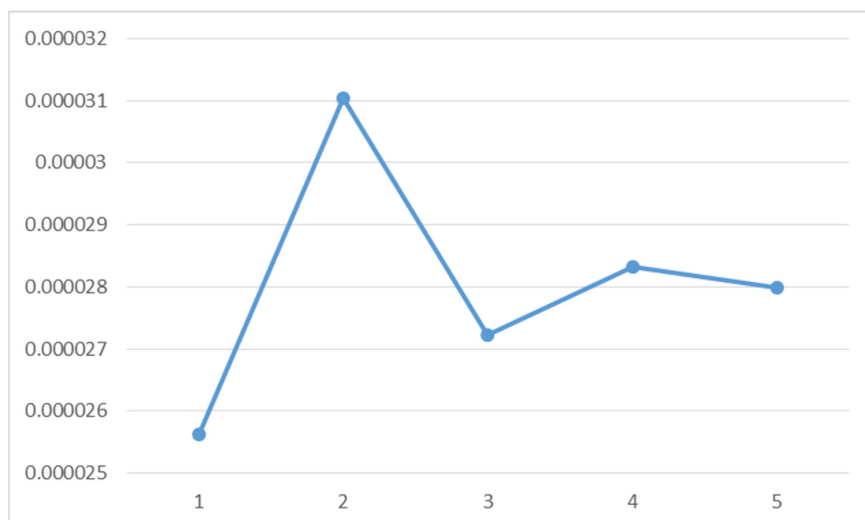


Figure 3. Mass of carbon emissions on a road section from a single vehicle for several alternatives, kg.

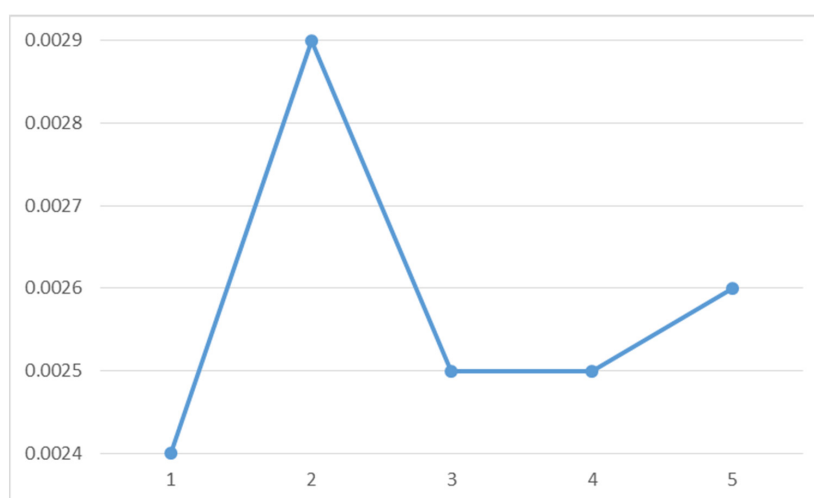


Figure 4. Mass of $C_{20}H_{12}$ emissions on a road section from a single vehicle for several alternatives, 10^{-6} kg.

The simulation results show the deviation of the masses of emissions of several pollutants on a small section with the same average speed and a slight difference in the structure of time spent in engine modes. The driving style can significantly affect the masses of pollutant emissions with similar average traffic characteristics. Using the engine load as a criterion and developing the proposed system for accounting for emissions will help overcome the limitations of approaches for assessing pollutant emissions by motor vehicles.

An illustration of the assessment of the effects of various alternatives to movement with similar averages of movement indicators shows the importance of an emission accounting system to improve the accuracy of estimating pollutant emissions for specific vehicles. The spread of the values of the mass emissions of pollutants by a motor vehicle at the same average speed demonstrates the importance and necessity of an emission accounting system in large cities. Such a system will improve the accuracy of the assessment of emissions in the city, ensure high-quality control and expand the possibilities of administration of various environmental protection tools.

3.3. System of Environmental Policy Instruments to Ensure the Internalization of Economic Damage from Actual Emissions of Pollutants by Motor Vehicles

At present, in order to satisfy short-term economic goals, conditions for the inevitable degradation of environmental quality have been created in many areas, since investments in reducing damage from pollutant emissions and the complete prevention of environmental pollution are economically unprofitable. However, the “political will” of the government, including as the owner of the assimilation potential of the ecosystem, is capable of accelerating the necessary changes for a gradual transition to sustainable development.

In order to significantly improve the quality of the environment in urbanized areas, it is necessary to focus on the significant impact of motor vehicles on ecosystems (taking into account other sources of negative impact). Given that the most effective and widespread utilizer of pollutants is the natural environment, in the long term, the main goal of the environmental policy of the territory can be defined as reducing man-made emissions to the maximum allowable load on the ecosystem [80,105]. Achieving this goal can be ensured by implementing a comprehensive environmental program with specific objectives and an effective system of tools for their implementation [3]. The specifics of local environmental problems can be taken into account by developing medium-term environmental programs at the regional and municipal levels, which, along with socio-economic ones, will be included as components in a comprehensive regional development program. In addition to an effective system of environmental policy instruments, such programs should include a number of specific measures to create conditions to improve the ecological situation of the territory. However, the solution of ecological problems should not prevent the satisfaction of the socio-economic needs of the region. It is necessary to achieve a balance of resource, ecological and social parameters of life for the transition to sustainable development.

The solution of environmental problems associated with motor transport should be singled out in a separate target program for the implementation of the environmental and economic strategy for reducing damage from emissions of pollutants by motor vehicles. One of the main goals of such a program can be considered the internalization of economic damage from environmental pollution by motor vehicles. Achieving this goal must be ensured in accordance with the concept of sustainable development, i.e., the transition to full internalization of damage from environmental pollution should occur without negative consequences for the socio-economic sphere. The program can be managed by both state and private structures. The main goal of such a structure should not be profit maximization, but the optimal redistribution of environmental fees and charges for environmental pollution for the purpose of improving its quality.

In order to internalize the economic damage from environmental pollution by motor vehicles, the environmental program must contain a system of environmental policy instruments that will allow for the collection of funds from vehicle owners for the actual economic damage caused by environmental pollution. A model of such a system is presented in Figure 5.

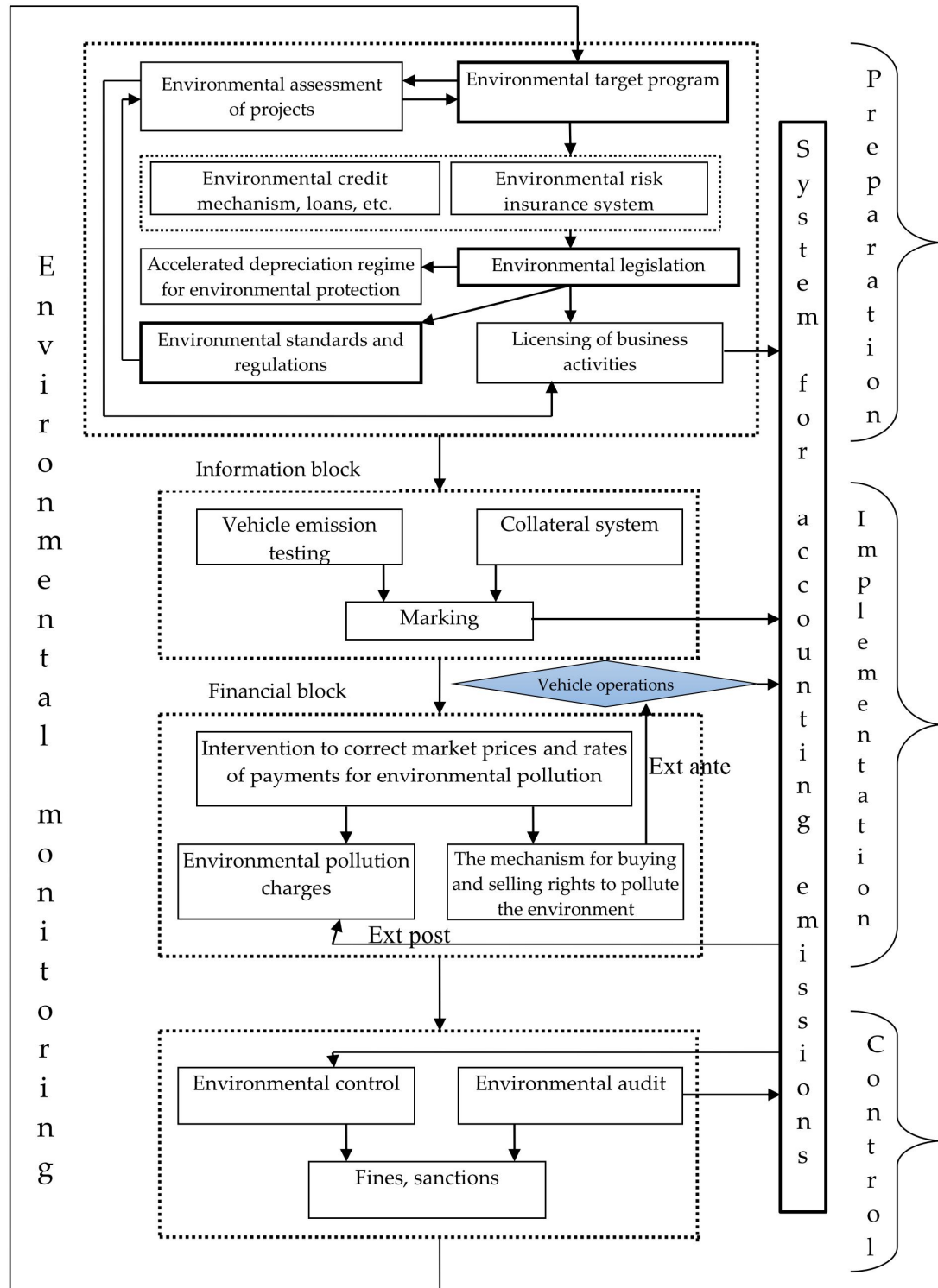


Figure 5. System of internalization of economic damage from actual emissions of pollutants by motor vehicles.

Based on the need to eliminate the negative consequences of the socio-economic development sphere, a gradual transition to environmentally acceptable loads on the ecosystem should be carried out. The transition to the internalization of economic damage from actual environmental pollution by motor vehicles in full should be carried out in several stages. Each of these stages contains three stages: preparation, implementation, and control. At the preparation stage, specific tasks are set and conditions for their solution are provided. At the implementation stage, an assessment and internalization of economic damage from environmental pollution by specific motor vehicles occurs. The procedure for monitoring objects that have a negative impact on the environment and the organizations servicing them is carried out at the third stage. The transition to the next stage will depend on the fulfillment of the set tasks. Let us consider in more detail the presented stages of the system of internalization of economic damage from actual environmental pollution by motor vehicles.

The main instrument of environmental policy of this system is the environmental target program, which sets specific tasks and necessary changes in legislation, describes the stages of its implementation, conditions for implementation and a set of environmental measures for which the funds received will be distributed. The entire range of tasks of the environmental program and the measures proposed for their solution must undergo environmental assessment, including the required changes in legislation.

The adequate use of the “polluter pays” principle implies responsibility for creating the conditions for environmental pollution [42]. When the system of internalization of economic damage from pollutant emissions for vehicle owners operates, the state bureaucracy should be economically interested in improving the quality of the environment and the efficiency of the territory’s transport system.

Administrative and control instruments of environmental policy (environmental standards and regulations, environmental certification, environmental control), together with economic measures (subsidies, tax incentives, information pressure, risk insurance, etc.), will allow for the transition to the production of more environmentally friendly vehicles.

Initial funding for such programs can be provided through borrowed or budgetary sources. It is also possible to ensure risks associated with achieving the planned effectiveness of the system of environmental policy instruments.

The accelerated depreciation regime for environmental protection equipment for motor vehicles will reduce its payback period and reduce some costs associated with the taxation of legal entities. Technologies capable of ensuring the production of more environmentally friendly motor vehicles should be equated with environmental protection equipment.

To begin implementing the program, it is necessary to establish initial environmental standards and regulations (taking into account their subsequent tightening).

Based on the regulatory documents, the licensing of economic activities of organizations involved in the calculation of environmental payments, and VET, as well as the environmental impact assessment of any economic entities that have a negative impact on the environment is carried out. Licensing of economic activities is based on the results of environmental assessment, which in turn is based on environmental standards and regulations of a specific territory.

Readiness for the “implementation” stage of the system of environmental policy instruments depends on ensuring the necessary changes in legislation and sufficient resources for their implementation, the possibility of fully satisfying the demand for environmental protection devices and environmentally friendly cars.

One of the main obstacles to the internalization of actual damage from environmental pollution by motor vehicles is information limitations—the problem of economic assessment of the negative impact of a specific vehicle. Let us consider this process in more detail.

To assess vehicle emissions, it is proposed to use the dependences of pollutant consumption in vehicle exhaust gases on the effective power. Such dependences for specific vehicles will allow for determining the VET, which can be carried out by vehicle manufacturers or special organizations with legislative consolidation in addition to the existing control procedures. The method of assessment and the system for accounting for actual pollutant emissions by vehicles on the territory are presented in more detail in Sections 2.1 and 3.1. To account for pollutants in vehicle emissions and subsequently calculate the appropriate fee, you can use a direct (direct measurement of the mass of pollutant emissions using sensors) and indirect method of assessing the toxicity of vehicle exhaust gases. The direct method assumes, on the basis of the emission accounting system, a transition to the internalization of damage from actual emissions of pollutants by motor vehicles using the mechanism of buying and selling rights to pollute the environment (for public and freight transport) and payments for polluting the environment.

The indirect method of accounting for pollutants in vehicle exhaust gases involves assessing the mass of pollutants neutralized by a device that reduces the toxicity of exhaust gases based on its service life during service replacement. Based on the VET and environmental protection characteristics installed on vehicles of environmental protection devices, it is possible to determine the total mass of pollutants in exhaust gases and their emissions into the environment. The indirect method of assessing the toxicity of vehicle emissions can be used as a control procedure or as the main tool for internalizing economic damage from environmental pollution. In the second case, the internalization tool can be a collateral system, within the framework of which the damage from vehicle emissions will be transferred to the price of the environmental protection device.

In order to stimulate the production of environmentally friendly products by compensating part of the costs (including by introducing a collateral system to compensate part of the costs of processing spent devices that reduce the toxicity of exhaust gases), it is necessary to use intervention to correct market prices. Also, by interfering with the functioning of the mechanism for the purchase and sale of rights to pollute the environment, it is easy to change the volume of permits for the emission of pollutants (regulate the quality of the environment) by buying out the corresponding amount of them.

The solution to the main tasks at the stage of “implementation” of the system of interaction of environmental policy instruments for the internalization of damage from actual emissions by motor vehicles can be reduced to synchronizing the work of all services involved in the calculation and collection of funds for the internalization of economic damage from actual emissions by motor vehicles and ensuring ease of control over the functioning system of environmental policy instruments.

In order to prevent violations of environmental regulations and the possible emergence of unscrupulous participants in the process of internalization of economic damage from emissions of pollutants by motor vehicles, a control system should be introduced. A device for accounting for the negative impact of vehicle exhaust gases on the environment can be imagined as a kind of “counter”, in the absence of which the violator should be fined in the amount of the potential maximum damage from the impact of motor vehicles on the environment (i.e., the amount of the fee should be set based on the maximum mass of toxic emissions of a specific vehicle during its actual stay in a given territory). Environmental control over compliance with the requirement for the presence of devices that reduce the toxicity of exhaust gases, VET and other standards of environmental legislation can be assigned to a special structure, delegated to existing services, or automated control can be provided using various monitoring tools.

Particular attention should be paid to regular environmental audits of organizations involved in the calculation of payments for environmental pollution, VET of motor vehicles,

as well as all economic entities that have a negative impact on the environment. At the same time, it is necessary to distribute control functions in compliance with the proportionality of powers and responsibilities. Sanctions and fines can influence unscrupulous participants in the process of internalization of economic damage from actual pollution of the environment by motor vehicles.

One of the main parameters for determining the effectiveness of environmental programs, as well as any environmental protection measures, is the quality of the environment. In this regard, reliable information on the environmental situation in the region is required to assess the results of environmental policy. Systematic environmental monitoring, including in-kind measurements and calculation methods for assessing environmental parameters, can provide the necessary data. The results of such studies must be covered in the media.

The considered system of environmental policy instruments allows for achieving the goal of transferring external costs of environmental pollution into internal decision-making by car owners, corresponding to the “polluter pays” principle and the concept of sustainable development. At the same time, the term of introduction of the considered system of environmental policy instruments should be based on its significance for reducing the negative impact of motor vehicles on the environment relative to alternative systems of environmental policy instruments and environmental projects, as well as economic feasibility within the framework of the transition to sustainable development [106] and the socio-economic policy of the region.

4. Discussion

When forming a system of environmental policy instruments, the determining factor is the reliability of the initial information, minimization of environmental and economic damage and total costs, as well as an adequate scientifically based economic assessment of reducing damage from ecosystem pollution [82,89]. The article considers the possibility of introducing a system for internalizing economic damage from actual environmental pollution by motor vehicles. The study proposes a system for accounting for the actual emission of pollutants by motor vehicles on the territory using mathematical models for calculating the mass of pollutant emissions by motor vehicles into the atmosphere, based on the experimentally determined VET dependencies of pollutant concentrations in exhaust gases on the engine load characteristics of each vehicle, and a mechanism for collecting the necessary information. In this regard, the known environmental policy instruments must be supplemented by the VET—determining the dependence of the mass of pollutant emissions with exhaust gases on the engine load characteristics. In fact, an adequate system of information support for decision-making to the concept of sustainable development should include an assessment of the maximum allowable load on the ecosystem [105], the actual mass of emissions on the territory and the economic damage from them. The emission accounting system can serve as an independent element of the environmental management system in the territory for the prompt comparison of environmental alternatives. If the initial data (actual characteristics of motor vehicles and their operation in the territory) is available, the accounting system allows for retrospective assessment of the dynamics of the effectiveness of existing environmental policy instruments.

The proposed system of environmental policy instruments allows for the internalization of damage from actual emissions by motor vehicles in the territory. The basis for the internalization system is the system of accounting for actual pollutant emissions from vehicles. It can also be used independently to reduce information limitations in making management decisions in the field of environmental protection, energy efficiency and increasing the sustainability of the territory as a whole. The use of the mechanism of buying

and selling rights to pollute the environment for public transport based on the proposed system of accounting for actual emissions can act as an additional instrument for regulating and distributing routes among carriers in the territory of cities.

A system for accounting for vehicle emissions of pollutants can be implemented for public and freight transport in many cities. The costs of the first stage of the emission accounting system for these categories of transport will be minimal. They come down to the integration of a database on the actual characteristics of vehicles and the operation of these types on the territory and the inclusion of a module for estimating the mass emissions of pollutants to determine emissions on a specific section of the city's road network.

The dependence of the concentration of pollutants in exhaust gases on the effective power, taking into account losses, is an important indicator for assessing the quality of a power unit, such as a car engine, for comparing alternatives and assessing the economic damage from pollutant emissions. This criterion can also be used for electric transport: the mass of emissions will correspond to the electricity consumption of an electric vehicle multiplied by the mass of emissions during the generation of a unit of electricity in the territory, taking into account the efficiency. In this case, the economic damage from emissions will be associated with the location of the emissions. It can be significantly less when generating electricity outside the city or in places with a low population density compared to using internal combustion engines.

Effective capacity can also be a criterion for internalizing damage to electric vehicles. In this case, the connection with the impact on emissions of electric vehicles in the territory will be determined based on the characteristics of electricity generation in the territory. Accounting for the energy consumed by a mobile source and assessing pollutant emissions per unit of power of electricity generation sources in the territory will allow us to determine the contribution to environmental pollution of a specific car and motor transport in general. Payment for energy consumption must be made taking into account the quality of the power unit. Effective capacity affects the volume of exhaust gases, and the quality of the power unit and the efficiency of its management affect the content of pollutants in the exhaust gases.

The type and quality of the power unit determines the damage from energy consumption for the same operating conditions. As a result, the proposed system for ensuring the internalization of damage will form incentives for choosing the most energy-efficient alternatives (travel alternatives, behavior models). Under these conditions, the efficiency criterion for evaluating and comparing alternatives will be such relative indicators as the mass of pollutant emissions per unit of generated or consumed power, taking into account the efficiency ($\text{kg}/(\text{kW})$) and the content of pollutants in a unit of exhaust gas volume per unit of generated power ($\text{kg}/(\text{m}^3 \cdot \text{kW})$).

The volume of emissions per unit of used capacity, taking into account losses, can serve as a criterion for the quality of a power unit, industry, territory in terms of sustainability for comparing alternatives, determining dynamics and trends. For motor vehicles, the consumed power depends on operating conditions and driving style. The system for accounting for actual emissions will improve the adequacy of comparing alternatives for moving passengers and cargo, including with electric transport and unmanned systems. The system for ensuring the internalization of damage from actual emissions will reduce distortions and create adequate incentives to reduce damage from emissions.

The proposed approaches may be the most attractive in large cities. The emission accounting system can be integrated into the existing city control systems. This will minimize costs. In addition, at the level of large cities, policy errors have more significant negative consequences. The conditions of information constraints and the complexity of predicting the consequences of implementing various environmental alternatives may

contribute to the adoption of suboptimal decisions at different levels of management (driver, capital, bureaucracy). Forecast errors, ignoring measurement and estimation errors, can lead to high opportunity costs, especially in large cities. For such facilities, it is especially important to develop an information system and, when other environmental alternatives are exhausted, to move to the internalization of damage from actual emissions of pollutants by motor vehicles.

Although the proposed approach allows solving a number of problems in reducing information restrictions on actual vehicle emissions and distortions of incentives for car owners, its implementation has a number of limitations and requires solving additional problems.

The limitations of the method used in the study to estimate vehicle emissions of pollutants determine the disadvantages of the proposed models for the emission accounting system and the system of environmental policy tools for internalizing the damage from vehicle emissions. The most significant error in calculating the mass of harmful substance emissions is caused by the dependence of pollutant concentrations in the combustion products on the load of engines, which differs in scientific sources. Theoretical data on toxicant content in emission products are typically based on large amounts of experimental information, but the accuracy of calculations depends most heavily on the technical parameters of each engine, the timing, and conditions of operation. The content of trace impurities in combustion product emissions varies significantly depending on the brand of engine, and the maximum range of their changes before and after major repairs for some pollutants can reach up to 60% [3]. The range of concentrations of pollutants in exhaust gases can be quite wide, depending on the load of a particular vehicle's engine. The values may vary depending on fuel quality, engine settings, age of the vehicle, climatic conditions, and other factors. Under these circumstances, the emission accounting system may produce errors and require clarification. The clarification of the dependence of the concentration of pollutants in the exhaust gases can be carried out using the proposed vehicle emission test (VET) or theoretical studies. Using the VET results of new vehicles to estimate emissions will allow for the determination of minimum values. In order to match the consequences of the actual operation of motor vehicles with these data, it is necessary to carry out either a clarifying VET or strictly regulate the repair and maintenance of motor vehicle engines.

The calculation of the costs of building and operating a system for internalizing economic damage from actual emissions of pollutants by motor vehicles is complicated by the many alternatives for its implementation and the possible effect of scale. Moreover, the system of accounting for emissions for public transport and trucks can be implemented on the basis of existing control systems in many territories now. The barriers to the implementation of the third and fourth stages today include information and resource limitations, a shortage of qualified personnel and insufficient attention from government authorities to the environmental safety of local areas, the strategy being implemented to reduce damage from emissions in the area and the development path as a whole. In addition, the development of devices for the implementation of the fourth stage requires significant financial costs. The necessary funds can be obtained by introducing economic instruments based on the proposed emission accounting system. The solution to the problem of VET to determine the dependence of the concentration of pollutants in exhaust gases on engine load can be carried out at different stages of the vehicle life cycle and transferred to the manufacturer. Moreover, vehicle owners should have the opportunity to clarify the VET results using an independent assessment for their vehicle. The development of long-term environmental programs and government orders can significantly affect the cost of emission meters. To resolve these issues, it is necessary to conduct a series of

experiments, the results of which will allow for assessing the costs of various alternatives necessary for building and operating such a system in the territory.

In addition to control over the requirements of environmental legislation, it is necessary to ensure, through monitoring, the receipt of reliable information on dynamic changes in the quality of the environment and, on the basis of this data, to determine the compliance of the planned and actual indicators of the functioning of the program for the internalization of economic damage from environmental pollution by motor vehicles for the stage of its implementation under consideration. The basis for tightening environmental requirements and introducing the internalization system as a whole may be an increase in the effectiveness of the conditions for the internalization of economic damage from emissions of pollutants by motor vehicles [106,107]. The collected funds should be directed towards environmental protection purposes, and with the greening of the tax system, they can replenish budgets at various levels.

In connection with the possible negative consequences for the socio-economic development of the region, the tightening of environmental requirements (for motor transport, etc.) and the transition to full internalization of economic damage from environmental pollution should be carried out gradually. The prerequisites for finding the optimal time and territorial framework for such a transition are the socio-economic and environmental situation in the region [54,92,108], the economic potential for creating conditions for the transition to new environmental standards, the attitude of the population to the corresponding changes [41,109] and the conditions for the operation of mobile sources (quality of roads and fuel, optimization of traffic, etc.).

The following tasks can be identified as areas for future research: developing a method for assessing vehicle emissions and refining pollutant concentrations based on the engine load for different vehicles, developing models for assessing the cost of emissions in relation to sustainable development goals, developing a model for formulating a strategy for reducing the damage caused by vehicle emissions, taking into account the environmental sustainability of the territory, and developing a mechanism for distributing responsibility among the participants in pollution.

5. Conclusions

The main elements of the system for ensuring the internalization of economic damage from actual emissions of pollutants environmental and natural resource legislation, a system of standards and regulations, and an environmental target program are the main instruments of environmental policy. These instruments of environmental policy define the institutional framework and strategy for internalizing damage from actual emissions of pollutants by road transport: goals are outlined (an acceptable level of impact of pollutants on the environment, the desired quality of atmospheric air and vehicles), and conditions for achieving them are ensured through a regulated legal framework (legislative consolidation of the functioning of specific instruments of environmental policy, implementation of certain environmental and control procedures, etc.). A systemic solution to the problem of internalization of the reduction in economic damage from actual emissions of pollutants by motor vehicles is achieved by a comprehensive target environmental program, which includes environmental policy instruments of different groups. The target environmental program includes a system of environmental policy instruments that allows for the payment of natural resource use for car owners, and provides a gradual tightening of environmental requirements.

In order to reduce the negative impact of motor transport on the environment, it is necessary to form an ecological and economic strategy towards sustainable development. A consistent definition of scientifically based environmental goals and ensuring the conditions

for their achievement will allow us to move on to solving specific problems of the target environmental program, which should include various instruments of environmental policy. One of the environmental measures to reduce the negative environmental impact of motor transport can be a system of internalization of economic damage from actual emissions of pollutants by motor transport. It is assumed that such a system, in addition to reimbursing environmental protection costs and the fiscal function of environmental payments (fees), will stimulate environmentally conscientious behavior of car owners. The feasibility of moving from indirect taxes for car owners to internalization of economic damage from actual emissions through emission payments is dictated by ensuring the conditions for the effective functioning of the system [107], the economic efficiency of the construction and operation of such a system (first of all, this is due to the system of accounting for actual vehicle emissions and their control on the territory) compared to other environmental alternatives.

As a result of the study, a system for ensuring the internalization of economic damage from actual emissions of pollutants by motor vehicles is proposed. It includes a system for accounting for the actual emissions of pollutants by motor vehicles in the territory based on mathematical dependencies of the actual masses of pollutant emissions with exhaust gases on the engine load. Known environmental policy instruments should be supplemented by the VET to determine the dependence of the masses of pollutant emissions with exhaust gases on the characteristics of the engine load. This will allow for the internalization of economic damage from emissions for trucks and public transport—by a mechanism for buying and selling rights to pollute the environment, for other vehicles—by emission payments.

An important tool for assessing the level of actual emissions of pollutants by motor vehicles is the implementation of the VET to determine the dependence of the concentration of pollutants in the exhaust gases. The study proposes to conduct a VET to identify the qualitative characteristics of cars by determining the dependencies of the concentration of pollutants in the exhaust gases on the effective power of the engine, taking into account the efficiency. This procedure is used at the implementation stage in the model of the system of internalization of economic damage from actual emissions of pollutants by cars. It is necessary to calculate the mass of emissions of pollutants during the operation of a vehicle. It can also be used to determine the compliance of the source of environmental pollution with the environmental standards imposed on the territory under consideration. Such a study of the quality of the car engine can be used for various environmental policy instruments and comparison of various alternatives.

To account for pollutants in vehicle emissions and subsequently calculate the corresponding fee, a direct and indirect method of assessing the toxicity of vehicle exhaust gases can be used. The direct method can be based on calculating the mass of vehicle emissions using an engine load metering device and VET data. It assumes that, based on the emission accounting system, we will move to internalizing the damage from vehicle emissions using the mechanism of buying and selling environmental pollution rights (for public and freight transport) and environmental pollution fees. In the case of using the indirect emission accounting method, the internalization tool can be a collateral system, within the framework of which the damage from vehicle emissions will be transferred to the price of the environmental protection device.

A significant share of pollutants emissions from the transport complex of cities comes from public and cargo vehicles. The proposed system allows for accounting for emissions from these categories of transport based on the information systems already existing in many cities. To account for pollutants emissions from passenger cars, the existing information systems in cities will require development. The proposed system of accounting for emissions can act as an independent element of the management system in the territory

and will allow for more effective solutions to sustainable development. It will increase the adequacy of comparing environmental alternatives, and will increase the effectiveness of operational management decisions to reduce the environmental footprint of the city's transport complex. The proposed system of environmental policy tools allows for the solution of the problem of organizing the internalization of damage caused by actual emissions of pollutants by motor vehicles in the territory. Overcoming the distortions of indirect estimates of damage from vehicle emissions using the proposed system will improve the adequacy of environmental incentives for car owners. The developed emission accounting system and environmental policy instrument system are important elements of the institution for internalizing the damage caused by actual emissions of pollutants by vehicles.

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Abbreviations

The following abbreviations are used in this manuscript:

VET Vehicle emission testing

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