

## Technological Re-Equipment of Road Transport Enterprises in the Context of Developing Technical Diagnostic Methods

Serhii Oleksiyko <sup>1</sup> • Oleksandr Govorov <sup>2</sup> • Mykola Venher<sup>1</sup> •  
Andrii Pecheniuk <sup>3\*</sup>

<sup>1</sup> Higher educational institution "Podillia State University" (Ukraine). Assistant Professor at the Department of Tractors, Automobiles, and Power Equipment.

<sup>2</sup> Higher educational institution "Podillia State University" (Ukraine). Associate Professor at the Department of Tractors, Automobiles, and Power Equipment, PhD in Technical Sciences, Senior Researcher.

<sup>3</sup> Higher educational institution "Podillia State University" (Ukraine). Associate Professor at the Department of Energy-Saving Technologies and Energy Management, PhD in Economics, Associate Professor.

\* **Corresponding Author**, e-mail: [anvaspe@meta.ua](mailto:anvaspe@meta.ua)

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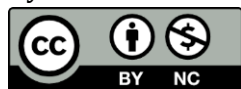
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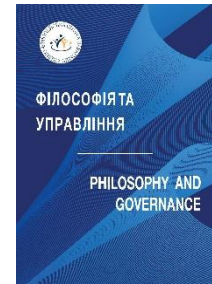
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The article investigates the comprehensive process of technological re-equipment of road transport enterprises through the prism of the evolution and implementation of the latest technical diagnostics methods. Key prerequisites and barriers (economic, technological, and personnel-related) hindering the industry's modernization are analyzed. The study highlights the historical retrospective of diagnostic tools development – from traditional instrumental control to modern cloud monitoring systems. Particular attention is paid to the practical aspects of production space reorganization within road transport enterprises. The impact of re-equipment on the efficiency of enterprise resource management is substantiated, specifically regarding inventory optimization, fuel efficiency, and the life cycle prolongation of the rolling stock. The transformation of the human factor's role, legal requirements for metrological certification, and environmental standards are examined as catalysts for change. The article outlines the futurological vector of the industry's development, which consists of the transition to the "digital twin" concept and predictive maintenance based on artificial intelligence. The social significance of modernization as a tool for the humanization of technical labor and increasing the overall level of road safety is proven.

### KEYWORDS

technological re-equipment, technical diagnostics, road transport enterprise, digital transformation, cloud technologies, digital twin, predictive maintenance, environmental safety.



## Технологічне переозброєння підприємств автотранспорту в контексті розвитку методів технічної діагностики

Сергій Л. Олексійко <sup>1</sup> • Олександр Ф. Говоров <sup>2</sup> •

Микола А. Венгер <sup>1</sup> • Андрій В. Печенюк <sup>3</sup> \*

<sup>1</sup> Заклад вищої освіти «Подільський державний університет» (Україна). Асистент кафедри тракторів, автомобілів та енергетичних засобів.

<sup>2</sup> Заклад вищої освіти «Подільський державний університет» (Україна). Доцент кафедри тракторів, автомобілів та енергетичних засобів, канд. тех. наук, старший науковий співробітник.

<sup>3</sup> Заклад вищої освіти «Подільський державний університет» (Україна). Доцент кафедри енергозберігаючих технологій та енергетичного менеджменту, канд. екон. наук, доцент.

\* Автор-кореспондент, e-mail: [anvaspe@meta.ua](mailto:anvaspe@meta.ua)

### СТАТТЯ

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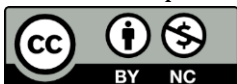
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У статті досліджено комплексний процес технологічного переозброєння автотранспортних підприємств через призму еволюції та впровадження новітніх методів технічної діагностики. Проаналізовано ключові передумови та бар'єри (економічні, технологічні, кадрові), що стримують модернізацію галузі. Висвітлено історичну ретроспективу розвитку діагностичних засобів – від традиційного інструментального контролю до сучасних хмарних систем моніторингу. Особливу увагу приділено практичним аспектам реорганізації виробничого простору автотранспортних підприємств. Обґрунтовано вплив переозброєння на ефективність управління ресурсами підприємства: оптимізацію складських запасів, паливну економічність та пролонгацію життєвого циклу рухомого складу. Розглянуто трансформацію ролі людського фактора, юридичні вимоги щодо метрологічної атестації та екологічні стандарти як каталізатори змін. Окреслено футурологічний вектор розвитку галузі, що полягає у переході до концепції «цифрового двійника» та предиктивного обслуговування на основі штучного інтелекту. Доведено соціальну значущість модернізації як інструменту гуманізації технічної праці та підвищення загального рівня безпеки дорожнього руху.



### КЛЮЧОВІ СЛОВА

технологічне переозброєння, технічна діагностика, автотранспортне підприємство, цифрова трансформація, хмарні технології, цифровий двійник, предиктивне обслуговування, екологічна безпека.

## 1. Introduction

The current state of the global economy and the rapid digitalization of production processes pose challenges to the transport industry that cannot be solved within the framework of outdated technical and operational paradigms. In this context, technological re-equipment becomes not just an element of modernization of fixed assets, but a fundamental condition for survival and competitiveness in the transportation market.

The key vector of such a transformation is the development of methods of technical diagnostics. If earlier diagnostics were perceived as an auxiliary operation to ascertain the fact of a malfunction, now it is becoming a strategic tool for resource management. The transition to the concepts of "Industry 4.0", the introduction of artificial intelligence and cloud computing systems, makes it possible to change the very philosophy of technical operation: from reactive correction of breakdowns to predictive (predictive) management of technical condition.

## 2. Literature Review

The analysis of modern publications indicates a profound transformation of approaches to the technical operation of cars under the influence of digitalization and the intellectualization of technical systems. In particular, fundamental approaches to strategic planning and technical development of motor transport enterprises are highlighted in the monograph by V.V. Bilichenko and E. V. Smirnov [2]. The authors emphasize the need for systematic renewal of the fleet and means of service. In turn, O. M. Lozhachevska and R. V. Grigorenko [13] provide a classification of services of a modern car service, which is the basis for understanding the volume of necessary technological re-equipment.

The development of diagnostic systems from traditional methods to modern standards is considered in detail by V. Zoshchak [24]. The issues of on-board diagnostics and the capabilities of the OBD system are analyzed by O. Sukhomlyn [19]. Scientists pay special attention to the improvement of express methods for monitoring the condition of engines [12; 22] and fuel equipment in urban service stations [14]. The complexity of diagnosing modern electrical systems is highlighted in the works of R. Dobrovolski [6].

Methodological approaches to the selection and operation of technological equipment for vehicle maintenance are presented in the works of O. A. Trigub [23]. Practical aspects of creating and planning service centers "from scratch" are considered by S. M. Hetmanchenko [8] and D. Demchyna [4], which is important for the formation of the optimal structure of diagnostic zones.

The scientific basis of modern intellectual technology is revealed in the manual on the basics of mechatronics by O. M. Artyukh et al. [1]. The processes of digitalization of logistics and the introduction of driver assistance systems are studied by M. Shtelmashuk [19] and M. O. Presnyakov [17]. A revolutionary direction is the integration of "digital twins", which is considered in the works of V. M. Pavlenko et al. [15] in the context of transport management and O. A. Filin [7] in the field of financial management of logistics.

The issue of effective use of personnel of a motor transport enterprise in the context of personnel shortages and war is studied by A. O. Blyzniuk [3] and A. Skrypal [18]. The problem of professional identification of service specialists is raised by O. Klymenko [11]. The impact of diagnostics on resource optimization, in particular forecasting the need for spare parts, is revealed in the work of A. A. Kashkanov and M. L. Moskalyuk [10].

Adaptation of European emission standards in Ukraine and methods for testing exhaust gas recirculation systems are the subject of research by V.M. Ivasenko [9], K. Shyrokun [20] and I. Polishchuk [16]. These works confirm the legal and environmental need to re-equip the diagnostic base.

The presented sources form a holistic picture of the transition from mechanical systems to cyberphysical ones. However, there is a need for additional research on the synergistic effect of the simultaneous introduction of digital twins and new organizational structures of diagnostic zones, which is the subject of this article.

## 3. Problem Statement

The purpose of the study was to substantiate the strategy of technological re-equipment of motor transport enterprises through the introduction of the latest methods of diagnostics and digitalization of

service processes. To do this, it was necessary to identify barriers to modernization, analyze the evolution of diagnostic tools from local devices to “digital twins” and develop a model of functional zoning of production areas. Particular attention was paid to assessing the impact of innovations on management efficiency, environmental safety and transformation of human resources in the context of intellectualization of the industry. The implementation of these tasks will allow us to form a holistic concept of the transition of a motor transport enterprise to a predictive model of technical operation.

#### 4. Methods and Materials

The methodological basis of the study was a systematic approach to the analysis of the processes of technical operation and technological re-equipment of motor transport enterprises. To solve the tasks, a set of general scientific and special methods was used: historical and logical – to track the evolution of diagnostic tools; analysis and synthesis – to identify barriers to modernization and formation of the structure of diagnostic zones; abstract and theoretical – to substantiate the concept “digital twin” and predictive maintenance.

The information base and materials of the study were the regulations of Ukraine and the European Union on environmental emission standards and transport safety, the results of scientific works of leading domestic and foreign scientists in the field of mechatronics, telematics and logistics. The empirical basis was the technical characteristics of innovative equipment for service centers and practical experience in the digital transformation of logistics processes. The combination of theoretical analysis of literature sources with the study of modern technological trends made it possible to ensure the reliability of the results and the validity of the proposed models of rearmament.

#### 5. Results and Discussion

In modern conditions, a technological revolution is taking place in the global transport industry. The familiar road transport enterprise (ATP) is transforming from a simple fleet of vehicles into a complex digital node of global logistics. In this context, technological re-equipment is not just a replacement of tools, but a deep transformation of the very structure of the business, where diagnostics becomes the “nervous system” of the whole organism.

In recent decades, global supply chains have been operating on a “just-in-time” model, where the vehicle is only a moving part of the assembly line. Any unplanned truck stops due to a minor sensor malfunction or bearing wear triggers a chain reaction of damage: factory line shutdowns, huge fines and loss of reputation. This means that the market no longer forgives “repairs after the fact”. Diagnostics should now perform a predictive function - it should ensure that the car will not only leave the pit, but also reliably cover thousands of kilometers without a single failure [5].

The current stage of development of the automotive industry is characterized by the deep integration of computing power into the design of the vehicle, which makes it possible to classify the modern car as a complex cyber-physical system. In the process of evolution, there has been a leveling of the clear boundary between hardware and software control algorithms.

The key feature of the modern element base is the transition to mechatronic units and assemblies [1]. Such systems are based on a synergistic combination:

- precision mechanics and hydraulic components;
- sensor networks for real-time monitoring of parameters;
- intelligent microprocessor control modules.

This transformation of the diagnostic object requires a revision of the paradigm of technological re-equipment of motor transport enterprises. Traditional maintenance methods are giving way to high-tech procedures, where the analysis of digital codes and logical sequences of software operation is as important as the control of the physical wear parameters of mechanical pairs.

The environmental requirements of Euro-6 standards and above have added another level of complexity. Exhaust gas neutralization systems are so sensitive that the slightest deviation in the quality of fuel or the operation of the injector instantly puts the car into “emergency mode” [20]. Without re-equipment to modern diagnostic methods, the mechanic remains “blind” in the face of such equipment, and the company becomes a hostage to the expensive assistance of official dealers.

Despite the obvious need, the rearmament process faces serious obstacles. These barriers can be divided into several fundamental layers.

The first and most obvious barrier is financial. A professional diagnostic line, which includes laser geometry stands, powerful brake testers and intelligent scanners, requires capital investments commensurate with the cost of a new long-haul tractor.

For many ATP owners, a psychological barrier arises: investing in one “iron” machine seems more understandable and liquid than investing in “invisible” diagnostics. The effect of rearmament is not an instant profit: it manifests itself in the form of deferred savings on fuel, tires and the absence of fines, which requires strategic thinking from management for years to come [4].

It should be noted that most Ukrainian fleets are multi-brand. One box can contain cars of different manufacturers and generations. A technological contradiction arises: each manufacturer protects its electronics with “digital locks”. At the same time, ATP is faced with the need to purchase either dozens of specific scanners for each brand or extremely expensive universal solutions that still require regular and paid subscriptions to updates [6]. This continuous cycle of software updates becomes a new type of operating cost for the enterprise, for which many are not ready either financially or organizationally.

The need to overcome the “human” barrier deserves special attention. In the current difficult conditions of Ukraine, there is a deep gap between generations of specialists. There are experienced mechanics on the market who hear the malfunction “with their ears”, but pass in front of the touch screen of a diagnostic tablet. On the other hand, there are young IT professionals who see error codes but do not understand the physical nature of the process in the engine cylinder [3]. Rearmament is often accompanied by internal sabotage. Employees fear that automation and digital transparency of diagnostics will deprive them of the right to “copyright opinion” (and additional unofficial earnings) or reveal their incompetence in working with digital systems.

The prerequisites for rearmament lie in the plane of business survival, while the barriers lie in the plane of psychology and outdated financial models. The technological renewal of ATP today is not only about buying a stand, but about overcoming internal resistance and moving to a culture where decisions are made based on data, not assumptions. An ATP that has data on the state of its equipment becomes less vulnerable to surprises on the road and market instability.

The development of diagnostic methods took place through consistent digitalization and distancing of control means from the object. This process can be structured into four key stages [24]:

1. Organoleptic and mechanical analysis. The initial period was based on the subjective experience of a specialist and the use of the simplest measuring instruments (pressure gauges, stethoscopes). Diagnostics were exclusively reactive in nature: it was carried out only after the actual manifestation of the malfunction, which was accompanied by significant repair costs.

2. Stationary instrumental diagnostics. With the advent of specialized stands (brake, traction and economic), control has become objective. This made it possible to implement the principles of non-destructive testing, evaluating the parameters of units under load without disassembly. This stage became the foundation of the classic system of scheduled preventive repairs.

3. On-board self-diagnosis. The massive introduction of microprocessor systems transformed the car into a source of digital data. The use of scanners made it possible to localize defects at the level of software algorithms and electronic circuits. Diagnostics has moved into the format of a “dialogue” between the hardware and the diagnostician.

4. Telematics and “cloud” technologies (predictive diagnostics). The modern stage is characterized by continuous data translation to cloud storage. The use of Big Data and artificial intelligence technologies allows you to create “digital twins” of units. This enables a shift to predictive maintenance – detecting critical wear well before a failure occurs.

Thus, the evolution of diagnostic methods has shifted the focus from ascertaining breakdowns to their mathematical prediction. Technological re-equipment of a modern ATP is, first of all, integration into the global digital ecosystem for real-time technical condition management.

The effectiveness of technological re-equipment of ATP is determined not only by the list of purchased equipment, but also by a fundamentally new logic of organizing the production space. The modern model provides for the transformation of the traditional structure of workshops into a system of specialized zones, each of which is integrated into a single digital control circuit [2].

The first stage of re-equipment is the creation of an express diagnostics zone, which operates on the principle of a “passage gateway”. Unlike traditional reception, where the inspection is carried out by a master, non-contact sensor systems are involved here. Real-time laser scanners analyze wheel geometry and residual tread depth, while smart cameras identify the vehicle and pull its digital history

from the database [12]. This allows you to instantly differentiate the traffic flow, separating cars that need immediate attention from those that are ready to go on a trip.

The central link of the re-equipped enterprise is a multifunctional diagnostic hub. Heavy bench equipment is concentrated in this space, which allows for non-destructive testing of safety and power transmission systems under load. The use of roller stands with built-in scales and hydraulic backlash detectors makes it possible to simulate real road conditions, detecting hidden defects in the suspension and brake system that cannot be detected during a static inspection [23]. This is the area where physical wear parameters are converted into accurate numerical readings.

The most innovative segment in re-equipment is the creation of an area for working with intelligent driver assistance systems. This is a “clean” zone, where cameras, radars and lidars are adjusted using laser targets and calibration stands. In this space, diagnostics finally moves away from mechanical manipulations, focusing on programming and verification of control algorithms [17]. It is here that the correct operation of emergency braking and adaptive cruise control systems is ensured, which is critical for modern safe transport.

Modern technological re-equipment is impossible without a chemical and technical analysis zone. The creation of a small but high-tech laboratory allows for express diagnostics of the “health” of the engine according to the state of its oil and fuel [22]. The use of compact spectrometers makes it possible to detect microscopic particles of wear metals, which is an early signal of future failure of the unit. This approach turns diagnostics into a method of in-depth examination, which avoids expensive aggregate repairs due to timely intervention.

The organization of workplaces within the diagnostic zones is based on the principles of mobility and information accessibility. Abandoning desktop computers in favor of rugged tablets and wireless diagnostic interfaces allows the specialist to stay at the center of the process, having instant access to the manufacturer's cloud services and technical maps. This minimizes time losses and increases the overall production culture, turning the ATP into a modern engineering center. The new architecture of diagnostic zones for technological re-equipment is aimed at creating a continuous flow of information about the condition of the vehicle. Clear functional zoning allows not only to increase the throughput of the enterprise, but also to provide such a level of accuracy that guarantees trouble-free operation in the conditions of increasing complexity of modern transport.

Technological re-equipment of ATP through the development of diagnostic methods leads to fundamental changes in the management structure of fixed and current assets. The traditional model, based on reactive defect correction, is giving way to an intelligent management strategy, where diagnostic data becomes the main tool for cost optimization.

The introduction of modern diagnostic systems allows you to move from the purchase of spare parts “in reserve” to a dynamic supply model. A modern car service enterprise has the ability to predict the residual resource of critical components (turbochargers, fuel system elements, transmission units). This radically changes the warehouse policy: significant working capital that was previously accumulated in excess inventories is released [10]. Resource management becomes point-by-point – the part is ordered and delivered at the exact moment when diagnostic indicators signal that it is approaching the extreme state of wear.

One of the most tangible consequences of rearmament is a direct impact on the fuel efficiency of the fleet. Microprocessor diagnostics methods make it possible to detect hidden deviations in the operation of fuel injection systems, valve timing and aerodynamic drag due to incorrect wheel alignment angles. Even a slight deviation, invisible during visual inspection, can lead to an overconsumption of fuel by 3-7%. On the scale of a large motor transport enterprise, accurate diagnostics of fuel equipment turns into a strategic resource for reducing the cost of transportation, providing a quick return on investment in diagnostic equipment [14].

Technological renewal changes the structure of labor costs. Automation of diagnostic operations in the entry control zones allows you to reduce the time for troubleshooting the car several times. However, this requires a redistribution of resources towards the intellectualization of personnel. Resource management now involves investments not only in hardware, but also in the constant professional transformation of personnel [18]. The mechanic turns into an operator of complex diagnostic systems, which increases the productivity of individual labor and reduces the likelihood of erroneous decisions that previously led to unjustified expenditure of time and money.

The use of methods of non-destructive testing and tribodiagnostics (analysis of working fluids) allows for significantly extending the service life of fixed assets without losing their reliability. This

creates conditions for flexible management of depreciation deductions. The company gets the opportunity to reasonably extend the service life of equipment that is in excellent technical condition according to digital monitoring data. This approach increases the capitalization of the business, since the market value of a car with a confirmed diagnostic history is much higher.

In modern conditions, compliance with environmental standards is not only a legal requirement but also an economic resource [16]. Accurate diagnostics of exhaust gas treatment systems avoids large penalties and provides unhindered access to international logistics markets. Thus, technological re-equipment converts environmental safety into sustainable development and competitive advantages of the enterprise.

It should be noted that technological re-equipment in the context of the development of diagnostic methods is not a purely internal production process. It is regulated by an extensive system of legal norms and international environmental standards, which determine the framework of legitimacy and competitiveness of the enterprise in the domestic and foreign markets.

Modernization of the diagnostic base requires strict compliance with the requirements for metrological certification. Any equipment used to assess the technical condition (especially in terms of traffic safety) must be entered into the relevant state registers and undergo regular verification.

From a legal point of view, the data of diagnostic stands are the basis for the formation of technical inspection reports and protocols for checking the suitability of vehicles for operation. The legal responsibility of the ATP for the reliability of this data increases in proportion to the complexity of the digital systems used.

The development of diagnostic methods allows documenting the park's compliance with the categories of "especially green and safe" (Euro-5, Euro-6) [8]. The legal aspect here is the legitimization of the right of access to the European market of logistics services. Without modern means of diagnostics of fuel equipment and gas purification systems, it becomes impossible to obtain appropriate international certificates, which actually blocks the foreign economic activity of the ATP. Modern diagnostics transforms environmental responsibility from passive fixation of emissions to active management of them.

A specific legal barrier of our time is the issue of ownership of data generated by the car. The technological renewal of the ATP poses a challenge to the management regarding the "right to repair". Equipment manufacturers often restrict access to service protocols through "Security Gateway" systems [21]. Legal support of rearmament includes the settlement of relations with the copyright holders of the software to ensure full access to diagnostic functions, which is necessary for an independent technical service.

The ecological aspect of re-equipment also covers the internal environment of the enterprise. The introduction of automated diagnostic complexes instead of traditional methods (for example, checking the engine under load in a closed box) reduces the level of noise and gas contamination in working areas. This contributes to the implementation of labor protection standards and increases the social stability of the enterprise, forming an image of "clean" and safe production.

The prospects for the technological re-equipment of the ATP lie in the plane of complete digitalization of the life cycle of the vehicle. Modern diagnostics is transformed from a discrete process (periodic checks) into continuous intelligent monitoring, the final form of which is the creation and operation of a "digital twin" of the car [19].

A digital twin is a dynamic virtual model of a physical object that reproduces its technical condition, performance characteristics and operating history in real time. Unlike a static database, a twin is constantly "fueled" by data streams from hundreds of onboard sensors and telematics modules. In the context of ATP retrofitting, this means moving from hardware analysis to virtual copy management, where any change in injector performance, tire pressure or oil temperature is instantly reflected on the digital model.

The main advantage of integrating diagnostics with digital twin technology is the possibility of predictive modeling [15]. Using artificial intelligence and machine learning algorithms, the system compares the current twin data with reference mathematical wear models. This allows not only to record the malfunction, but to "play" scenarios of the future state: for example, to calculate the probability of turbocharger failure while maintaining the current driving style and environmental conditions. Diagnostics is turning into a tool for strategic anticipation of events.

It is to be expected that the car of the future will independently "initiate" diagnostic cycles, identify anomalies, and, in the event of software failures, carry out automatic correction of control algorithms.

In case of physical deterioration, the “digital twin” autonomously interacts with the logistics system of the enterprise: it reserves the necessary part in the warehouse, assigns a visit to the service area, and forms the terms of reference for robotic service stations [7].

The development of diagnostic methods will lead to the creation of global databases where information from the “digital twins” of millions of cars will be used by manufacturers to improve designs. For ATPs, this means a shift to the data economy. A transparent, digitally verified operating history is becoming a valuable asset that radically changes approaches to assessing the residual value of machinery, insurance, and leasing.

It should be noted that the technological re-equipment of ATP, despite its technical and economic nature, has a deep social resonance. The development of diagnostic methods radically changes not only production indicators, but also working conditions, professional standards and the prestige of technical professions in modern society.

Modernization of the diagnostic base brings the work of personnel to a qualitatively new level. The traditional image of the mechanic, whose activities were associated with hard physical labor and an aggressive production environment, is becoming a thing of the past. Modern diagnostics is the intellectual work of the operator of complex systems. The use of wireless interfaces, tablets and robotic stands makes the workplace ergonomic and clean. This not only reduces the level of occupational diseases, but also changes the psychological climate in the team, fostering responsibility for the accuracy of data, and not for the speed of “force” repair [13].

One of the most acute problems of the transport industry is the aging of personnel. Technological re-equipment is a powerful stimulus for the influx of young people. Modern graduates of technical universities are focused on working with digital technologies, IT interfaces and artificial intelligence [11]. The creation of modern diagnostic centers on the basis of ATP, reminiscent of high-tech laboratories, makes the industry attractive for a new generation of engineers. This ensures the heredity of knowledge and the integration of academic education into the real sector of the economy.

The social significance of rearmament also lies in the protection of human life and health. Automation of troubleshooting processes (for example, the use of backlash detectors or brake test stands) minimizes the risks of injuries during the inspection of rolling stock. In addition, an accurate diagnosis of the environmental parameters of each vehicle has a direct impact on the quality of life in the community where the business is based. Reducing the level of noise and emission toxicity through system control is a significant contribution of ATP to the sustainable development of the region and the social well-being of the population [9].

A modern car diagnostics company is forced to invest in the intellectual development of its employees, organizing advanced training courses, certification training, and training in working with updated software. This contributes to the overall growth of the educational level of specialists in the region, increasing their social mobility and competitiveness in the labor market.

The final social product of the modernization of the ATP is to improve the safety of all road users. Professional diagnostics allows you to exclude the human factor when assessing critical nodes. The social mission of the re-equipped ATP is to create such a system of technical control that guarantees the preservation of the lives and health of citizens due to the trouble-free operation of transport.

## **6. Conclusions**

Summing up the results of the study of the processes of technological re-equipment of motor transport enterprises in the context of intensive development of technical diagnostic methods, it can be argued that modern industry modernization has gone beyond the simple replacement of physical equipment. It has been transformed into a deep system restructuring, where digital data on the condition of the vehicle becomes the main economic and operational asset of the enterprise.

Evolutionary analysis of diagnostic tools has made it possible to establish that the transition from on-premises controls to global cloud platforms radically changes the paradigm of technical service. Instead of the traditional elimination of defects that have already occurred, modern retrofitting offers a predictive control model based on the anticipatory detection of critical wear. This not only increases the reliability of transportation but also turns diagnostics into an intelligent filter that ensures continuous fleet performance in real time.

An important result of the work is the substantiation of the new architecture of the production environment of the ATP. The introduction of specialized express control zones and calibration areas for

intelligent driver assistance systems allows you to integrate the physical space of the enterprise into the manufacturer's digital ecosystem. Such organization of processes minimizes the impact of the human factor at the stage of entry control and ensures the compliance of the fleet with strict legal and environmental standards, in particular Euro-6 requirements, which is critical for entering international logistics markets.

A promising vector outlined in the study is the transition to the use of “digital twins” as the highest form of diagnostic monitoring. This technology allows you to convert the physical parameters of operation into a virtual model, providing accurate forecasting of the remaining life and optimization of spare parts costs. The social significance of such modernization is manifested in the humanization of engineering work and increasing the prestige of professions in the transport industry, which together create a reliable foundation for sustainable development and trouble-free operation of modern road transport.

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