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# RESEARCH ON DEVELOPMENT TRENDS OF TRANSPORT VEHICLE STRUCTURES BY FORECASTING TIME SERIES OF PATENT DATA

# ДОСЛІДЖЕННЯ ТЕНДЕНЦІЙ РОЗВИТКУ ВАНТАЖНИХ ТРАНСПОРТНИХ КОНСТРУКЦІЙ ШЛЯХОМ ПРОГНОЗУВАННЯ ЧАСОВИХ РЯДІВ ПАТЕНТНИХ ДАНИХ

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**Abstract.** This article presents the main approaches to forecasting developments in freight wagon designs based on the analysis of time series of patent information, which is the most informative source of data for long-term technical forecasting due to its systematic nature, chronological completeness and detailed classification according to the headings of the International Patent Classification. *Purpose*. The aim of the article is to justify approaches to forecasting the development of freight wagon designs based on patent information, to refine the mathematical framework for forecasting patent activity, and to determine the critical level of innovation quality at which patenting is economically viable. *Methods*. Modern methods of processing patent information are analysed: thematic modelling using the LDA algorithm, network analysis and time series forecasting using the ARIMA model. An improved econometric procedure for forecasting the number of patent applications is proposed, which takes into account research and development expenditure, intellectual capital, the number of people employed in the scientific sector, and the level of intellectual property rights protection. *Results* were obtained: a five-factor econometric model of the number of patent applications was developed; relationships were derived for the discounted value of future profits in the presence of a patent; and a critical level of innovation quality was substantiated. Based on data for the Ukrainian railway carriage manufacturing sector, the number of applications stands at ≈409, and as the quality of innovation increases, this figure decreases in accordance with an inverse exponential relationship. *Scientific novelty*. A shift has been observed from increasing metal content towards composites, modular platforms and digital diagnostic systems. The scientific novelty of the results lies in the development of an improved econometric model for forecasting the number of patent applications, which comprehensively takes into account R&D expenditure, intellectual capital, human resources and the level of intellectual property rights protection, and also enables the critical level of innovation quality to be substantiated. *Practical*

*importance* of the research lies in the possibility of using the model to formulate scientific and technical strategies for railway wagon manufacturing enterprises and to justify the feasibility of patenting new technical solutions.
**Key words:** freight wagons; patent analysis; forecasting; time series; development trends; ARIMA; LDA; econometric modelling.

**Анотація.** У статті розглядаються ключові підходи до прогнозування розвитку конструкцій вантажних вагонів, опираючись на аналіз часових рядів патентної інформації, така інформація є довгостроковим прогнозування завдяки своєїй систематичності, хронологічній повноті та детальній класифікації в рамках Міжнародної патентної класифікації. *Метою* дослідження статті, обґрунтувати підходи до прогнозування розвитку конструкцій вантажних вагонів, використовувати патентну інформацію для вдосконалення математичного апарату прогнозування патентної активності та визначення критичного рівня якості інновацій, при якому патентування має економічний сенс. *Методи*. Проаналізовано актуальні методи обробки патентної інформації, зокрема тематичне моделювання за алгоритмом LDA, мережевий аналіз та прогнозування часових рядів через модель ARIMA. Запропоновано покращена економетрична процедура прогнозування кількості патентних заявок, яка враховує витрати на дослідження й розробки, інтелектуальний капітал, кількість зайнятих у науковій сфері, а також рівень захисту прав інтелектуальної власності. *Отриманні такі результати*: розроблено п'ятифакторну економетричну модель кількості патентних заявок; отримано залежності для дисконтованої вартості майбутніх прибутків за наявності патенту; обґрунтовано критичний рівень якості інновацій. На даних для вагонобудування України кількість заявок становить ≈409 одиниць, а зі зростанням якості інновацій вона зменшується за оберненою експоненційною залежністю. Встановлено перехід від нарощування металоємності до композитів, модульних платформ і систем цифрової діагностики. *Наукова новизна* отримані результати полягають у розробленні удосконаленої економетричної моделі прогнозування кількості патентних заявок, яка комплексно враховує витрати на R&D, інтелектуальний капітал, кадровий ресурс та рівень захисту прав інтелектуальної власності, а також дозволяє обґрунтувати критичний рівень якості інновацій. *Практична значимість* дослідження полягає у можливості використання моделі для формування науково-технічних стратегій підприємств вагонобудування та обґрунтування доцільності патентування нових технічних рішень.
**Ключові слова:** вантажні вагони; патентний аналіз; прогнозування; часові ряди; тенденції розвитку; ARIMA; LDA; економетричне моделювання.

## STATEMENT OF THE PROBLEM

The modern development of transport engineering places increased demands on the technical level and competitiveness of freight cars. Identifying promising directions for the development of structures is an important scientific and applied task. Patent information is a unique source of data for predicting technical development due to its systematicity, chronological completeness and detailed classification according to the headings of the International Patent Classification (IPC). Analysis of the entire array of patent information allows us to trace not only the evolution of structures, but also to determine the state for a certain period and identify prospects [1]. The relevance of the chosen research topic is determined by the fact that forecasting the designs of cars allows us to determine the direction of research work, modernization of car designs in general.

## ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

One of the important stages of research and determination of trends, current and prospective level of railcar products is the analysis of patent search. Patent research is regulated in Ukraine by the state standard DSTU 3575-97. It establishes the basic provisions and procedure for conducting patent research.

The issue of predicting the technical level of railway transport facilities has been the subject of work by many researchers. This article [2] presents an analysis of the dynamics of patenting gondola body designs over a 20-year period in leading countries. The dynamics of patenting gondola body designs has been studied, and the main directions of their modernization have been identified. It has been established that the average development time in the production of patented technical solutions for improving wagons is 20 years.

In this study [3], the authors apply the Latent Dirichlet Allocation (LDA) algorithm to thematic modeling of patent data related to the piggyback transportation system (transportation of trailers by rail). Using the ARIMA model to forecast the time series of the identified topics, the paper identifies promising technologies, including integrated data-driven management systems and special cargo processing technologies, demonstrating the effectiveness of combining text mining and time series to shape R&D strategies.

The article [4] offers an analysis of the development of digital technologies that are fundamentally changing the competitive dynamics in the logistics industry. For its participants, digitalization is becoming a necessary condition for survival and sustainable development. A key role in the technology strategy is played by identifying opportunities and threats through the analysis of technological trends. Unlike previous studies that relied on expert assessments or simple trend identification

through thematic modeling, this work offers a new framework for developing a technology roadmap.

The authors of [5] focus on identifying "vacant" (promising but not yet patented) technologies for a truck-on-rail platform transportation system (TFTFT). Using GTM (Generative Topographic Mapping) and network analysis of USPTO patents, they identify two key vacant areas: the technical field of rail vehicles suitable for TFTFT and equipment for cargo handling. This allows them to formulate a technology development strategy.

Article [6] is devoted to defining promising directions of designing load-bearing systems of freight cars. The author proposes a method of implementing various profiles as component elements, which allows to increase the efficiency of structures and improve their technical characteristics.

The study [7] focuses on predicting the development of two-axle bogie designs for freight cars. The authors develop approaches to identifying trends in the technical characteristics of running gear, which is important for increasing the reliability and durability of rolling stock.

This study [8] highlights the results of work on identifying ways to increase the degree of ideality of freight cars and predicting the next generations of evolution of their supporting systems. The article also presents examples of the application of the idealistic-oriented strategy proposed for freight cars to improve the supporting systems of universal railway gondolas.

This is a fundamental study [9] that establishes a link between patent activity and economic productivity in OECD countries. The authors developed models to estimate the impact of patenting on economic growth, which laid the foundation for further research in the field of innovation economics.

This paper [10] examines the issues of international patenting, the impact of patent rights on technological development, and the analysis of technological gaps between countries. The author analyzes how different intellectual property regimes affect international technology transfer and innovation activity.

In the article [11] it is proposed to equip the platform wagon with rotating fitting stops. This technical solution allows using the same platform for transporting both 20-foot and 40-foot containers without the need to change the frame design. This is a classic example of the implementation of the "body-designer" principle (adaptive platform).

In the article [12] the traction reducer mounting bracket, which is one of the elements of the running gear of the metro rolling stock, is inspected. The features of its design and possible malfunctions that may occur during operation at the stages of the product's life cycle are indicated.

## IDENTIFICATION OF PREVIOUSLY UNRESOLVED PARTS OF THE GENERAL PROBLEM

To achieve the goal, it is necessary to solve the following tasks:

1. To substantiate the feasibility of using patent information as the main source for long-term forecasting of the development of technical systems in railcar construction.

2. To analyze modern methods of processing patent data (LDA thematic modeling, network analysis, ARIMA) and determine their suitability for identifying promising areas for improving designs.

3. Improve the mathematical apparatus for predicting patent activity by introducing an indicator of the qualitative level of innovation (q) and a coefficient that takes into account the costs of patenting and the degree of protection of intellectual property rights.

4. Develop an econometric model (5-factor) to quantify the impact of R&D spending, intellectual capital, human resources, expected profits, and the level of patent protection on the number of patent applications.

5. Determine the critical level of innovation quality ($q$), which justifies the economic feasibility of patenting technical solutions in the field of freight car construction.

## RESEARCH OBJECTIVE

Patent information is the most valuable material for predicting the designs of a technical system, such as a gondola body, due to its specificity, novelty, reliability, concentration, and completeness of information about the technical essence.

Conducting patent research is important for budgetary institutions or organizations that are partially financed from the state budget. Mathematical methods of calculating and analyzing the patent fund allow us to assess the development trends of an object of technology. With the help of these methods, directions for improving designs are determined, including long-term trends, as well as those that have exhausted their potential. Some patents were also cited for research [13–18].

Analysis of the entire array of patent information allows us to trace not only the evolution of designs, but also to determine the state for a certain period and identify prospects. To identify existing gondola body designs, a patent search was conducted in the following countries: Germany, the USA, the EU, China, Canada, Ukraine and Russia. A search for technical information was also conducted in magazines, bulletins, and directories of the above-mentioned industrially developed countries. The depth of the patent search was determined by the research objectives: identifying trends and identifying the most promising developments. The use of patent information is based on the fact that a patent application is implemented in 10–12 years in the first sample and in another 8 years in

serial production. As a result of the analysis, it was found that the average development time in the production of patented technical solutions for improving gondolas is 17–20 years [16, 17].

## METHODS, OBJECT AND SUBJECT OF RESEARCH

The object of the research is the process of technical development of freight car load-bearing structures, reflected through the dynamics of patent activity in leading engineering countries. The subject of the research is the forecasting of patent applications for freight car designs based on time-series analysis. This includes thematic modelling (LDA), network analysis and ARIMA-based forecasting. The main attention is paid to the relationship between R&D expenditure, intellectual capital and innovation quality on patent application volumes.

## MAIN MATERIAL

The distribution of patent searches is valuable information, but it only gives a generalized idea of patenting by search country; more valuable information is the directions of improving railcar designs according to patents.

Analysis of the entire array of time series of patent data allowed us to draw conclusions about the development trends of materials and design. At the beginning of the analysis period, the main focus was on increasing strength and load-bearing capacity by increasing metal content. Today, the trend has changed:

– lightweight composites and alloys, patents aimed at reducing the body's own weight (tare weight characteristics). Use of aluminum alloys and composite materials instead of traditional steel.

– Modularity: Patenting of universal platforms ("body-constructor"), which allow the car to be quickly transformed for the transportation of different types of cargo.

– Aerodynamics: With increasing speeds, patents appeared for streamlined body shapes to reduce the fuel (or electricity) consumption of the locomotive.

Digitalization and automation

The main change of the last 10 years is the integration of "digital" into «hardware»:

– Smart unloading systems: Locking mechanisms with remote control and position sensors (patents for IoT in railcar construction).

– Built-in diagnostics: Patents for bodies equipped with built-in sensors for deformation, cargo temperature monitoring, and structural wear [15–18].

– Autonomous driving: Patents related to the adaptation of the body and chassis for unmanned control.

Comparative analysis of patent activity of leading countries in the development of freight car designs in Figure 1.

Body design: Integration of load-bearing elements (the end pillar is integrated into the upper belt) to reduce metal consumption and simplify assembly. Integration with the skin: this design allows the side wall skin to "enter" the cutout, creating a continuous load-bearing system where the elements do not overlap, but work as a single unit.

– Cleaning hatches: A massive series of patents on curved hinges that ensure the lid is fixed in the open position (critically important for the safety of unloading bulk cargo).

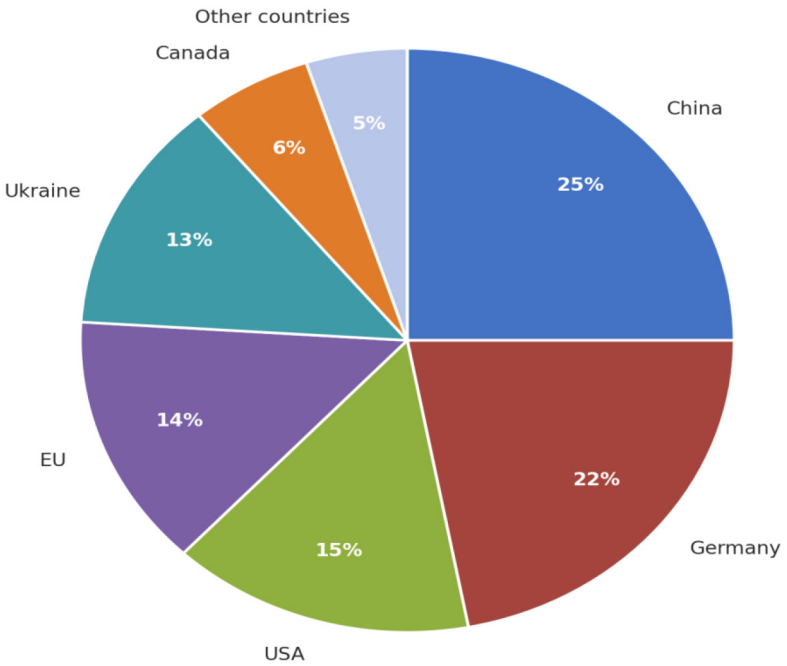



**Fig. 1.** Comparative analysis of patent activity of leading countries in the development of freight car designs

– Locking mechanisms: Transition to simplified lever systems with a straight rod to increase reliability.

The patents are aimed at modernizing and strengthening existing structures (corrugated beams), and not at creating fundamentally new types of cars. Engineering solutions are aimed at increasing the volume of the body while maintaining dimensions (increasing load capacity) and improving unloading mechanisms (remotely controlled hatches). Passenger car with corrugated beams in the supporting structure Strengthening the supporting structure of the body through the use of corrugated beams (corrugated beams) in the ridge and cross beams.

The main objects of modernization of the gondola body are the walls (side and end), frame, removable roof and skin. Regional priorities of engineering solutions were distributed as follows: in other regions and Ukraine, the emphasis was on the introduction of various forms of profiling; in the USA and China – on developed roof profiles; in Europe – on streamlined body shapes; in Canada – on improving the skin.

The analysis of patents was carried out on the basis of the so-called patent numbers, which show the distribution of patent documents over time. The quantitative characteristics of the dynamics of the studied direction can be determined by various methods, the most famous of which is the calculation of the so-called dynamics coefficients (dynamics curves), the value of which characterizes the intensity of a certain direction. Considering forecasting at the macro level (in the national economy), it should be noted that in foreign practice much attention is paid to the construction of predictive mathematical models. These models gained wide popularity abroad in the 1990s in the works of J. Eaton and S. Kortum, as well as Walter J. Park [19].

In their models, they used the costs and benefits associated with filing patent applications as factors influencing the number of patent applications. In our view, these were more important to the patent office and other stakeholders than to the national economy as a whole.

However, in 2005, U. Abdih and F. Joguts [20] managed to adapt the production function to forecasting purposes.

In general terms, the mathematical model for determining the number of patent applications in a national economy is written as follows[1]:

$$P_i = \alpha \cdot R_i^{\beta_1} \cdot S_i^{\beta_2} \cdot L_i^{1-\beta_1-\beta_2} \cdot F_i, \quad (1)$$

where: $\alpha > 0$, $R_i$ – the value of intellectual capital (knowledge, skills and intangible assets, including patents, databases, software, trademarks, etc., which are productively used to maximize profits and other economic and technical results [19]),

$P_i$ – the number of patent applications in the i-th country (region);

$R_i$ – the amount of research and development costs;

$S_i$ – intellectual capital;

$L_i$ – the number of people employed in research and development;

$F_i$ – a coefficient that takes into account the costs of patenting and the degree of copyright protection;

$\alpha$ – scaling factor;

$\beta_1$, $\beta_2$ – elasticity coefficients showing how many percent the number of patent applications will change if the corresponding factor changes by 1 %.

To determine $F_i$, the concept of the qualitative level of innovation ($q$) is introduced – an indicator that reflects the practical value of developments, and the growth of labor productivity and income due to their implementation is exponentially dependent on this factor.

Profit after patenting innovative developments is defined as:

$$\pi = h \cdot \exp(q) \cdot \pi_0, \quad (2)$$

where: $\pi$ – expected profit after patenting;

$\pi_0$ – basic profit excluding innovation;

$q$ – qualitative level of innovation (the higher $q$, the more significant the innovation);

$h$ – coefficient that takes into account the risk of borrowing technology ($0 \le h < 1$);

$\exp(q)$ – exponential function of $q$.

If we denote by $\theta$ – the increase in the level of individualization of innovations due to copyright protection, and $r$ – the real interest rate, then the discounted value of future profit streams in the presence of a patent will be: $\theta r$

$$V^{ЗАХ} = \int_0^{\infty} (h+\theta)\pi_0 \exp(q)\exp(-rt)\,dt = \frac{(h+\theta)\pi_0 \exp(q)}{r}, \quad (3)$$

where: $V^{ZAG}$ – the discounted value of future profits if patent protection is available;

$t$ – time;

$\exp(-rt)$ – a discount factor that reduces the value of future income.

Accordingly, without copyright protection (in the absence of a patent), i.e. $\theta = 0$, the effect of copyright protection can be written as follows: $\theta = 0$

$$\Delta V = V^{zag} - V^{noy\ zag} = \frac{(h+\theta)\pi_0 \exp(q)}{r} - \frac{h\pi_0 \exp(q)}{r} = \frac{\theta\pi_0 \exp(q)}{r} \ge C, \quad (4)$$

where: $\Delta V$ – additional effect of patenting;

$V^{noy\ zag}$ – the discounted value of future profits in the absence of a patent;

$C$ – costs associated with patenting (cost of bench and practical tests, state fees, etc.).

Using the resulting equations, the critical quality level of innovation can be determined as follows:

$$q^* = \ln\left(\frac{r \cdot C}{\theta \cdot \pi_i}\right), \quad (5)$$

where: $q^*$ – critical level of innovation quality, above which patenting becomes economically feasible;

The critical level shows that only the number of patents for the most valuable and practically significant developments should be taken into account when forecasting, and the stricter the patent legislation, the lower this threshold.

The coefficient $F_i$ in this case is determined by the equation:

$$F_i = \exp\left(-\psi q^*\right) = \left(\frac{rC_i}{\theta_i \pi_i}\right)^{-\psi}, \quad (6)$$

where: $\psi$ – sensitivity coefficient;

$C_i$ – costs of patenting in the i-th country;

$\theta_i$ – the level of rights protection in the i-th country;

$\pi_i$ – expected profit in the i-th country.

By substituting expression (6) into formula (1) and taking the logarithm, we can reduce the final equation to the following form:

$$\ln\left(\frac{P_i}{L_i}\right) = a_0 + a_1 \ln\left(\frac{R_i}{L_i}\right) + a_2 \ln\left(\frac{S_i}{L_i}\right) + a_3 \ln\left(\pi_i\right) + a_4 \ln\left(\theta_i\right) + a_5 \ln\left(C_i\right) + \xi, \quad (7)$$

where: $a_0$, $a_1$, $a_2$, $a_3$, $a_4$, $a_5$ – regression coefficients;

$\xi$ – random error of the model;

ln – natural logarithm.

Thus, a 5-factor model was obtained for determining the number of patent applications. To demonstrate the calculations, we will assume the following values for Ukraine according to Table 1.

Number of patent applications () for transport structures (freight wagon) $P_i$ According to formula (1). First, we calculate the power components:

$$R_i^{\beta_1} = 500^{0,4} = e^{0,4 \cdot \ln(500)} = e^{0,4 \cdot 6,2146} = e^{2,4858} \approx 12,01;$$

$$S_i^{\beta_2} = 300^{0,3} = e^{0,3 \cdot \ln(300)} = e^{0,3 \cdot 5,7038} = e^{1,7111} \approx 5,53;$$

$$1 - \beta_1 - \beta_2 = 1 - 0,4 - 0,3 = 0,3;$$

$$L_i^{0,3} = 1000^{0,3} = e^{0,3 \cdot \ln(1000)} = e^{0,3 \cdot 6,9078} = e^{2,0723} \approx 7,94;$$

$$P_i = 0,05 \cdot 12,01 \cdot 5,53 \cdot 7,94 \cdot 15,49;$$

$$P_i = 0,05 \cdot (12,01 \cdot 5,53 = 66,42) \cdot (7,94 \cdot 15,49 = 123,01);$$

$$P_i = 0,05 \cdot 66,42 \cdot 123,01 = 0,05 \cdot 8170,5 \approx 408,5.$$

The projected number of patent applications is ≈ 409 for the estimated period.Table 2 to analyze the impact of the qualitative level of innovation $q$ on the number of patent applications, the values of Fi ($q$) and Pi ($q$) were calculated in the range of $q$ from –6 to 0 with a step of 1.

**Table 1.** Data for calculating the number of patent applications according to the given mathematical model

| Marking | Parameter | Value | Units of measurement |
|---|---|---|---|
| $\alpha$ | scaling factor | 0.05 | – |
| $R_i$ | research and development costs | 500 | million UAH |
| $S_i$ | intellectual capital | 300 | mental unit |
| $L_i$ | number of people employed in R&D | 1000 | persons |
| $\beta_1$ | elasticity coefficient for $R_i$ | 0.4 | – |
| $\beta_2$ | elasticity coefficient for $S_i$ | 0.3 | – |
| $\theta_i$ | level of rights protection | 0.6 | – |
| $C_i$ | patenting costs | 50 | thousand UAH |
| $\pi_i$ | expected profit | 2000 | thousand UAH |
| $r$ | real interest rate | 0.10 | – |
| $\psi$ | sensitivity coefficient | 0.5 | – |

**Table 2.** Analysis of the impact of the qualitative level of innovation q on the number of patent applications

| $q$ | exp($q$) | $F_i = \left(\frac{rC_i}{\theta_i \pi_i} \cdot \exp(q)\right)^{-\psi}$ | $P_i$ |
|---|---|---|---|
| –6.0 | 0.00248 | 27.36 | 722 |
| –5.0 | 0.00674 | 20.08 | 530 |
| –4.0 | 0.0183 | 14.74 | 389 |
| –3.0 | 0.0498 | 10.82 | 286 |
| –2.0 | 0.1353 | 7.94 | 210 |
| –1.0 | 0.3679 | 5.83 | 154 |
| 0.0 | 1.0000 | 4.28 | 113 |

The graph in Fig. 2 reflects an inverse exponential relationship: with increasing innovation quality $q$, the number of patent applications $P_i$ decreases, since there are objectively fewer high-quality innovations, but each has greater practical value.

## DISCUSSION OF THE RESULTS OBTAINED

The analysis demonstrates that the modern development of railcar construction is characterized by a change in priorities from extensive strength enhancement to intensive improvement of technical and economic parameters of rolling stock. The key vector is orientation towards the requirements of the consignor, who determines such parameters as load capacity, body volume, axle load, design speed and mileage between overhauls. The infrastructure component, in turn, ensures the adaptation of the railway infrastructure to implement these requirements.

Technological progress is reflected in the creation of wagons with increased axle load (25 and 27$t$), which allows to significantly increase the load capacity. In

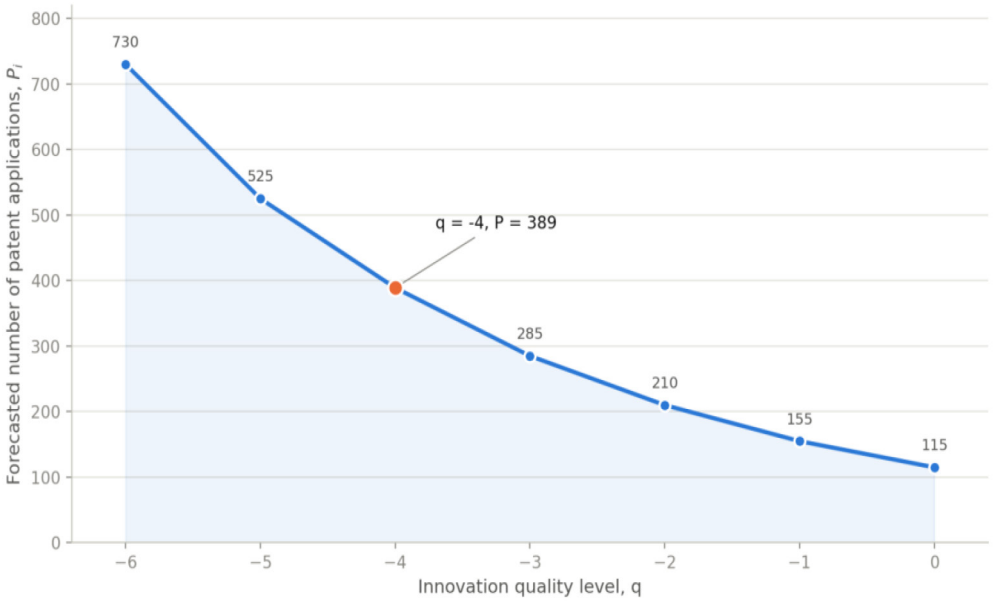



**Fig. 2.** Dependence of the forecast number of patent $P_i$ applications for transport structures on the qualitative level of innovations $q$

parallel, the running gear is being improved – new models of bogies with cassette-type bearings and increased wear resistance of elements are being introduced, which directly affects durability. A significant achievement is the increase in mileage before the first scheduled overhaul from 210 to 500 thousand km, and between overhauls – up to 250 thousand km, thanks to the use of components with improved characteristics (T1 class shock absorbers, brake pads with a service life of up to 250 thousand km, autocouplers with increased wear resistance).

## CONCLUSIONS

The structural evolution of bodies is manifested in the transition to a "skeleton design" and modularity. Replacing the traditional backbone beam with frameless teardrop-shaped structures (for example, developed by the Kryukivka Wagon Building Plant) allows you to reduce the number of parts, reduce metal corrosion and speed up unloading. The introduction of articulated platforms provides a doubling of the mass of the transported cargo while reducing operating costs. A separate trend is the integration of load-bearing elements (for example, an end post with an upper belt), which reduces the number of welds in stress concentration zones and increases the service life between overhauls.

Patent activity in recent decades indicates a shift towards securing not individual parts, but complex technological platforms that combine lightweight materials, integrated architecture and built-in electronics. There is an increase in the number of solutions for "smart" diagnostic systems (strain, wear, temperature sensors) and remote unloading control. At the same time, there is a differentiation of strategies: leading manufacturers focus on fundamentally new types of wagons, while in some regions patent activity is limited to the modernization of the existing fleet.

Thus, a promising direction is the further intellectualization of structures, the expansion of the use of lightweight composite materials and high-strength steels. The introduction of unified modular wagons, which allow for flexible adaptation of rolling stock to changing operating conditions and market needs.

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