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The Fourth Industrial Revolution and its Impact on Railways

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ABSTRACT

The analysis of the stages of development of industrial production by human society based on the well-known concept of four industrial revolutions has resulted in retrospection of technical and technological development of railways during the periods between the industrial revolutions in terms of core rail engineering systems (infrastructure, rolling stock, control and management system), as well as contributed to outline prospects for foreseeable period. It has allowed to identify main directions of technical and technological development of productive forces characteristic of the fourth industrial revolution.

The objective of the research was to identify those directions that are appropriate to be applied in relation to rail transport as well as to choose a few specific technical and technological solutions.

In the field of digitalisation, it is proposed to focus on development and implementation of intelligent management systems for each workplace or of intelligent workplaces (IWP), which ensure development of optimal solutions for numerous operational tasks fulfilled by the dispatchers on duty at railway facilities. It has been determined that for a case of a large rail company like JSC Russian Railways creation of managers' IWPs should be based on the scale and generality of the tasks solved at numerous similar managed objects since, for example, the number of dispatching sections reaches more than 400, the number of stations and simultaneously moving trains is of several thousand, and of train sheds and infrastructure sections is of several hundred, etc. This allows creating standard systems that are further replicated for specific workplaces while considering local specifics.

Intelligent systems integrate as important elements fast-growing production of increasingly miniaturised, and to be underlined, constantly cheaper sensors, capable today of being built into almost any objects that in terms of railways comprise, for example, a wheel of a wagons or of a locomotive, engines, rails, any wagons or containers. This allows continuously monitoring the current state of any objects, as well as their nodes resulting in fundamentally new opportunities for reducing the cost of maintenance of rolling stock and infrastructure, as well as ensuring transport safety. Thus, for the first time ever, the task of achieving «absolute» rail traffic safety can be set.

The article includes a forecast of the approximate time of the advent of the fifth industrial revolution and the trajectories of development of technical systems of railways for the period before its start. The use of the results of the study is supposed to facilitate to concretise directions of the promising technical and technological development of rail transport.

Keywords: industrial revolutions, railways, intelligent workplaces, new jobs, robotics, forecast.

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INTRODUCTION

Mass production manufacturing industry on our planet started in the late 1700s, first in England. And then periodically there were technical and technological leaps which are known as industrial revolutions [1].

According to the accepted classification, four such revolutions have already taken place, the last of which is taking place today. Each of the revolutions is identified by new directions of development, based primarily on achievements of fundamental sciences, as well as by its own technical and technological achievements.

The *objective* of the article is to analyse new solutions that are characteristic of the fourth industrial revolution, as applied to rail transport. These solutions simultaneously define new tasks that transport science must solve in the modern period.

RESULTS

Retrospective Analysis

The first industrial revolution started during the second half of the 18th century and continued through the first half of the 19th century [1]. Its technological basis was founded by invention of steam engine followed by mechanisation of manufacturing process. Rail transport was among the most important components of the first industrial revolution: a steam locomotive appeared, and the already existing mostly wooden rails were quickly replaced with cast iron ones.

Railway employees can be proud of the fact that it was this mode of transport that connected the cities with convenient ground transit, which ensured not only rapid industrial growth in the 19th century, but also fundamentally changed the life of the human community. Railways, with a total length of more than 1 million km on five continents [2], still fulfil this role today, and so far, there is no replacement for them. But what about the car? The answer is simple. In a car, you can't carry ore for 2000–3000 km or more. It is expensive. Yes, transportation of such mass cargoes as crude oil, gasoline, over long distances has mainly switched to pipelines, because it is cheaper. But there are hundreds of types of oil products. And practically each of them requires its own pipeline. With relatively small volumes of production, their construction is economically unjustified. Therefore, transportation of most of them is carried out by railways. It is the possibility of cheap transportation over long distances of mass and other goods, that makes railways so far indispensable. At least for the next 100 years or more.

The second industrial revolution began closer to the end of 19th century [3] with industrial exploration of electricity, adoption of new steelmaking technology, and flow-line production. Railways began to switch to electric traction (electric locomotives). During the same period, an internal combustion engine, a car, airplanes, diesel locomotives and much more appeared.

The 1960s saw another radical change with the advent of semiconductors and computers. Everything developed rapidly: first large computers appeared, then, in the 1980s, personal computers and in the 1990s the Internet emerged. It was the third, computer or otherwise digital revolution.

Fourth Industrial Revolution and Railways

Today we are at the beginning of the fourth industrial revolution. This is not fully understood by society yet, but it is true. What is it?

Each new technological transformation lays on previous advances. The fourth industrial revolution relies primarily on the digital revolution, fundamentally developing it based on the transition to intelligent control systems, i.e., there should be a transition from automated workplaces (AWP) to intelligent workplaces (IWP). Without waiting for creation of artificial intelligence, similar to human intelligence, which, in our opinion, is still far away, it is necessary to create many «smart» objects using control algorithms close to those currently used. For rail transport, these are «smart» track, locomotive, wagon, train, station, container yard, train shed, industrial and social buildings, numerous «smart» objects of operational dispatch control [2–4]. And, finally, this is a «smart» railway, a «smart» department in the Russian Railways HQ, and

[1] Periodisation of the first industrial revolution has not been unambiguous till now. Different sources reference ots beginning either to 1740s or to 1760–80s.

[2] According to the UIC data the length of railways worldwide in 2020 exceeded 1 mln 140 thous km. [Electronic resource]: https://uic.org/IMG/pdf/passenger-tonne-line-kilometers-timeseries-overperiod-2004–2020.pdf. Last accessed 25.10.2022.

[3] Periodisation of its beginning and end time is also not unambiguous and can refer to different periods starting form 1870s.

even a «smart» manager within the top management of Russian Railways, no matter what position he holds, up to the highest one. In the end, most management decisions at all levels should (and undoubtedly will) be made by employees not only based on their knowledge, experience, intuition and just the mental abilities of a particular person, but mainly based on decisions developed on-line by intelligent management systems at specific IWPs. Such systems should be created by transport science, which today offers, as a rule, systems for solving individual problems or only information systems.

Of course, it is impossible to assign a research team to each facility or manager, but on the railway, creation of specific intelligent management systems that solve the entire large range of tasks at each individual workplace is facilitated by the mass character, large scale and typicality of tasks solved in the company, as well as the number of similar controlled objects and dedicated employees focused on the same task. For example, the number of simultaneously moving cargo trains is more than 2 thousand, locomotives are counted also in thousands, there are more than 1 million wagons, hundreds of train sheds and infrastructure sections, up to 400 train sections, thousands of stations. That is, the standard systems being created can be replicated, of course, considering local specifics. In general, the problem is extremely complex, and technologists (including practitioners), mathematicians, and programmers should participate in its solution. But the effect should be huge.

Firstly, this is an increase in the quality of decisions made, especially operational ones, since more factors will be considered than the capabilities of the brain allow. Moreover, in an operational environment, seconds may be allotted for decision-making, and then a person uses only intuition and accumulated experience.

Secondly, the factor of influence of difference in abilities of decision makers (DM) is excluded. An intelligent system in all cases must ensure the adoption of an optimal solution or of a solution close to it.

Thirdly, areas controlled by one manager are significantly expanding. The released staff can participate in research related to the expansion of work on the creation of IWP. And it is possible to reduce the duration of the working day and duty shifts.

All this will give the economic and social effect necessary for introduction of intelligent systems.

The most important element that ensures creation of intelligent systems and «smart» objects is associated with various sensors that are rapidly developing and becoming more and more miniature and cheap [5–7]. They are already capable of being built into any objects today, including, for example, a rail, a wagon wheel, a container, etc., allowing continuously monitoring the current state of any object and its nodes. And this opens completely new possibilities for ensuring traffic safety and personal safety on railways, as well as reducing maintenance costs.

It is interesting and important that for the first time in the history of technology, the issue of achieving «absolute» traffic safety in railway transport can be stated and resolved. At the same time, the influence of the human factor on occurrence of emergencies will be excluded by intelligent control systems, and the control of the reliable state of equipment will be provided by sensors at «smart» objects.

The fourth industrial revolution is not limited to fundamentally new developments in technology.

There are more and more new materials, the properties of which until quite recently could not have been imagined [8–10]. And it is difficult to predict what else will be achieved here.

In general, new materials are already becoming significantly stronger, lighter and more recyclable. New materials can significantly increase modulus of elasticity, static and dynamic strength, wear resistance of parts, and hence operational life of railway equipment. «Smart» materials will have memory and the ability to return to their original form, i.e., self-repair and self-purify. «Smart» crystals will turn pressure into energy, and so on.

Railway science should closely follow such achievements of fundamental science to adapt them in a timely manner to the needs of rail transport. And it is also possible to identify real technical requirements for creation of new materials that consider features of railway technology to the maximum. It is necessary that, i.e., JSC Russian Railways carries out research on the forecast of the use of new materials.

Today, such a direction as robotics is also rapidly developing [11; 12] based on increasing flexibility and adaptability of robots, the use of which is increasingly penetrating many industries. This is facilitated by mentioned miniature sensors, which provide monitoring of the state of both the objects themselves and the external environment.

In rail transport, there are many objects where robots can be used. For example, the term «automated hump yard» is known. But to prepare a train for disassembling in the arrival park of the marshalling yard, a team of wagon inspectors manually unhooks the sleeves of the air hoses of the wagons and checks their technical condition «crawling» under each wagon. And on the hump, one of the main operations for uncoupling the cars is carried out manually by the employees responsible for coupling and uncoupling of automatic couplers. Moreover, the maximum speed of disassembling, according to the condition of personal safety of employees, is limited to 7 km/h, although in the absence of such a restraint it could be 1,5–2 times higher. Now is the time to develop a truly «automated hump yard» without any restrictions on dissolution speed, based on robotisation of processes on the hump, as well as maintenance of trains in the arrival park. And this will give a greater effect due to the increase in the processing capacity of humps. There is no doubt that robots can be widely used in track repair, and within other railway facilities.

It is possible to name other directions of a fundamentally new development of technologies that ensure implementation of achievements of the fourth industrial revolution. For example, the use of unmanned vehicles [13] will be further extended to inspect infrastructure[4]. Also we can name the 3D, 4D printing, the technology of which can be used to manufacture various spare parts on site or close to the place of their use. Also, with the help of geolocation [14], it is possible to track the location of specific workers on railway tracks, preventing them from entering dangerous zones and promptly notifying them of the approach of trains, locomotives and shunting trains, etc.

Fifth Industrial Revolution: Tentative Conceptualisation of its Contents and Forecast of the Terms of its Beginning

Publications have appeared quite recently that are focused on forecasting of the contents and terms of beginning of the fifth industrial revolution. Thus, the authors [15] note that «the Fifth Industrial Revolution, or 5IR, encompasses the notion of harmonious human–machine collaborations, with a specific focus on the well-being of the multiple stakeholders (i.e., society, companies, employees, customers)» [15, P. 199] and that «The 5IR differs from the 4IR in its focus on synergistic collaboration rather than competition (and possible replacement). That is, in the 4IR, the goal was to increase the scope and number of innovative technologies in manufacturing as well as service and retail settings, such that humans and robots competed for jobs, and the use of technology was maximized. In the 5IR, shifting emphases instead prioritize efforts to understand where each actor excels and how humans and technology can collaborate, rather than one replacing the other» [15, P. 201]. Another author has described this process even more vividly: «Industry 5.0 will be about the robotics we put inside ourselves – bionic augmentation and the 'internet of bodies'»[5]. Another author in the paper entitled «In the 5th Industrial Revolution, creativity must meet technology» notes that «Like Industry 4.0, which focusses on the use of Artificial Intelligence (AI), Big Data and the Internet of Things (IoT), Industry 5.0 embodies these systems and incorporates greater human intelligence. The main difference between the 4th and 5th industrial revolutions is that Industry 5.0 seeks to foster a more balanced working relationship between increasingly smart technologies and humans. Rather than humans competing with robots for jobs, as feared with the arrival of Industry 4.0, humans are now envisioned to collaborate with them»[6]. Other authors referring also to educational process in the Universities outline that the fifth industrial revolution «will see humans leverage the technological gains of Industry 4.0, which was focused on automation, artificial intelligence, Big Data and the Internet of

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[4] How the unmanned vehicles work on railways [*Kak bespilotniki sluzhat na zheleznoi doroge*]. Gudok newspaper, November 11, 2022. [Electronic resource]: https://gudok.ru/content/infrastructure/1618875/. Last accessed 06.11.2022.

[5] Ball, C. How the fifth industrial revolution will impact the future of work. October 24, 2022. [Electronic resource]: https://www.theceomagazine.com/business/innovation-technology/fifth-industrial revolution/. Last accessed 06.11.2022.

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Table 1

Values of IR_i and $\Delta T_{i,i}+1$ for $IR_{1,2}$

IR_i	Calendar year (approximately) of the beginning of industrial revolutions	Time lag, years $\Delta T_{i,i+1}$
1	1805	85 for $IR_{1,2}$
2	1890	70 for $IR_{2,3}$
3	1960	50 for $IR_{3,4}$
4	2010	

Things, and transform them into human-centred solutions to a vast range of challenges»[7].

The concept of creation of intelligent workplaces described above fully comply with this approach and can be considered as one of directions of the fifth industrial revolution for rail transport. However, it is quite probable to expect fundamentally new technical and technological solutions that will cardinally change our impression on the nature of development of the new industrial revolution.

Let us now look a little into the future and try to determine the date of the possible start of the fifth industrial revolution, which requires an analysis of the nature of the change in the length of time passing from the beginning of one such revolution to the beginning of the next.

Let us designate the number of the industrial revolution as IR_i, while for the first of them $IR_1 = 1$, and accordingly, $IR_2 = 2$, $IR_3 = 3$ and $IR_4 = 4$. The length of time between adjacent industrial revolutions (time lag) $\Delta T_{i(i+1)}$ will be:

$$\Delta T_{i,\,i+1} = \Delta T_{(i+1)} - T_i, \quad (1)$$

where $T_{(i+1)}$, T_i, – calendar year of the beginning of the i-th and of the $(i + 1)$-th industrial revolutions.

Table 1 presents data on the approximate (estimated) calendar year of the beginning of industrial revolutions (basing primarily on their impact on the rail vehicles and technology) and the values of $\Delta T_{i,\,i+1}$.

Certainly, the years indicated in the Table, let us emphasise it once again, are conditional and are focused on key dates of the most expressive effect exerted by the first and second industrial revolutions on the rail transport. Thus, 1805 is the time of the intensive work on development of steam locomotives. 1890 is benchmarked as a conditional reference date, a median boundary of emergence of new railway technology. The Siemens company demonstrated in 1879 at the industrial exhibition in Berlin a first prototype of an electrified railway, while first electrified railway was commissioned for commercial operation, as it is deemed, in 1895–96 in the United States. The impact of the third and fourth industrial revolutions on railways can be counted from their very beginnings since the influence of revolutionising technologies emerged historically at once.

It is worth noting, whilst it is not shown in further estimations, that even if we take different dates of the beginning of the industrial revolutions irrespectively of railways, the common trend towards shortening of time lags is quite evident. If in the absence of commonly recognised terms of beginning of the first and second industrial revolutions, we shall deem the advent of the first industrial revolution to be in 1780, and the start of the second one in 1880 (without speaking about the eventual start, as it proposed sometimes, of the fourth industrial revolution at the early 2000s), then the time lags will be respectively of 100, 80, 50 years.

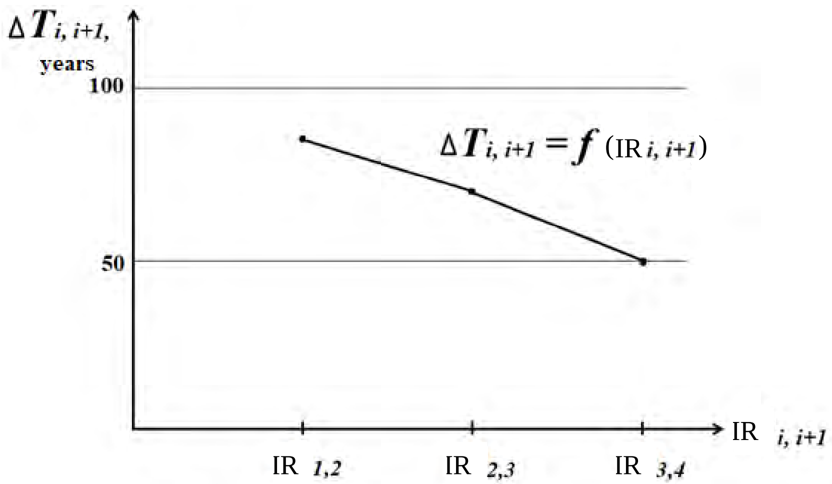
Thus, to some extent, considering the shortened time lags between industrial revolutions, synchronisation of their advent and the impact there-of on railways, futuristic character of the forecast, it can be also considered in terms of the beginning of the fifth industrial revolution as well.

Pic. 1 shows the function of change ($\Delta T_{i,\,i+1}$) of the time lag between adjacent industrial revolutions – here the numerical values $IR_{i,\,i+1}$ should be determined by the start time of the $(i + 1)$-th industrial revolution. Respectively: $IR_{1,2} = IR_2 = 2$, $IR_{2,3} = IR_3 = 3$, $IR_{3,4} = IR_4 = 4$.

Representing the desired function by a polynomial of the second degree, we obtain:

$$\Delta T_{i,\,i+1} = 100 - 2{,}5 \bullet IR_{i,\,i+1} - 2{,}5 \bullet IR^2_{i,\,i+1}. \quad (2)$$

[7] Preparing students for the fifth industrial revolution. Website of University of Technology Sydney, May 17, 2022. [Electronic resource]: https://www.uts.edu.au/news/education/preparing-students-fifth-industrial-revolution. Last accessed 06.11.2022.



Pic. 1. Function of the change of the time lag between adjacent industrial revolutions.

It would seem that extending the effect of dependence (2) to the period after $IR_{3,4}$ it is possible to determine the next time lags between industrial revolutions. But this issue must be approached very carefully. It is easy to see that function (2) can have zero and even negative values, which $\Delta T_{i,\,i+1}$ cannot take.

Assuming the possibility of extending function (2) for only one more period, i.e., before the start of the fifth industrial revolution, we get $\Delta T_{4,\,5}$ = 25 years. Then, for the accepted conditions, we can expect the start of the fifth industrial revolution in about 25 years, i.e., in 2010 + 25 = 2035.

Certainly, this forecast of the terms is not more than a probable variant of eventual development considering conditionality of the assumed time values.

As for duration of the validity of new technical and technological solutions of each of the industrial revolution, it can take almost any value. The shorter is this period, the faster the achievements of the next industrial revolution are implemented at the objects of the considered managed range which can be the whole country or its regions, continent (Europe, Asia, etc.) or even the whole earthly civilisation. The implementation period depends on many factors: the initial technical and technological state of the considered managed area, the financial situation, the system of social structure, etc. But it is ultimately determined by investment resources that can be used within the considered managed area.

Retrospective and Prospective Analysis of the Technical and Technological Development of Railways

The analysis of achievements of industrial revolutions that have already taken place and of the prospects for future new ones allows us to present a retrospective of technical and technological development of rail transport from the very first moment to the present and to forecast such developments for some future period. Table 2 shows such aggregated data for industrialised countries.

CONCLUSION

Sometimes you can hear the opinion that the age of railways is gradually ending. It's not like that at all. If the latest achievements of science are introduced in railway transport, then the scope of the use of railways will not only be preserved, but also expanded. This was proved, for example, by specialised passenger high-speed railway lines, HSR [16; 17]. At speeds up to 300–400 km/h and at distances up to 1000 km and even more, the travel time between the centres of large cities using high-speed lines takes less time than when using air transport. And indeed, where high-speed lines are built, and there are more than 59 thousand km[8] of them in the world today, passengers massively switch from air and road transport

[8] International Union of Railways. High-Speed Rail Atlas. 4th Edition: August 2022, P. 16. [Electronic resource]: https://uic.org/IMG/pdf/uic-atlas-high-speed-2022.pdf. Last accessed 06.11.2022.

Table 2

Enlarged description of the management system and development of the technical and technological state of railways per periods of industrial revolutions for industrialised countries

Railway transport management system	Technical and technological state of main devices		
	Track and track economy	Locomotives and wagons	System for ensuring train traffic and performing shunting work
Between the 1st and the 2nd industrial revolutions (approximately 1805–1890 years)			
• autonomous management of individual lines, later limited to railway networks	• cast-iron rails (weighing 25 kg/m), later steel; • gradual increase in rail mass; • wooden sleepers; • joint track; • manual track repair.	• steam traction (steam locomotives); • two-axle and less often 4-axle wagons; • speed up to ~60 km/h.	• telegraph communication; • token system; • semaphores; • manual switching; • mainly backing-up wagons.
Between the 2nd and the 3rd industrial revolutions (approximately 1890–1960 years)			
• transition in many countries to management of railways at the state level	• special steels for rails; • rail mass up to 40–50 kg/m; • continuous welded rail; • track machines for track maintenance	• electric locomotives; • diesel locomotives; • pneumatic brakes; • automatic coupler; • 4-axle wagons; • specialisation of wagons; • speed up to ~200 km/h.	• automatic blocking; • traffic lights; • radio communication; • centralised control of switches and signals; • section dispatching; • hump yards
Between the 3rd and the 4th industrial revolutions (approximately 1960–2010 years)			
• interstate information systems with single databases; • international transport corridors; • world container network; • specialised passenger and cargo lines.	• increase of wear resistance of rails; • rail polishing and grinding; • overhaul life up to 1 bln tons; • reinforced concrete sleepers; • «endless» rails; • tiled, monolithic base of the track; • automation of diagnostics; • bridges and tunnel crossings through sea straits; • mechanical track repair.	• lines and networks (Japan, Europe, China) at speeds up to ~300–350 km/h; • asynchronous engines; • electro-pneumatic brakes; • deep specialisation of wagons.	• dispatching centres for train traffic control at networks long of up to 56 thousand km; • fibre optic communication; • beginning of digitalisation; • automation of hump yards, parallel dissolution of trains.
Forecast after the 4th industrial revolution (option with close cooperation of the countries of the world) (approximately 2010–2035)			
• further development of international transport corridors; • expansion of containerisation of cargo transportation; • world information network; • deep cooperation between public and private railways.	• use of lighter and wear resistant new materials for rails; • bringing overhaul life to 2,5 bln tons; • new ballastless track structures; • automated complexes for track maintenance and repair.	• use of new types of fuel for locomotives (hydrogen, etc.); • wide use of automatic train control systems; • deepening the specialisation of rolling stock; • auto uncoupling.	• wide introduction of intelligent workplaces (IWP) of the dispatcher on duty; • interval traffic control without traffic lights; • significant increase in the number of consolidated dispatch centres.
	Implementation of systems for monitoring and diagnosing technical means of railways, ensuring achievement of «absolute» train traffic safety.		

to railway, because the speed and comfort of the trip are higher.

The same is true for the fourth industrial revolution. If its achievements are mastered, then new opportunities will appear for expanding the scope of the use of railways. If other modes of transport go ahead in mastering its achievements, then the role of railway transport may decrease.

The fourth industrial revolution that has begun opens new prospects and sets fundamentally new tasks for transport science. There is a wide field of activity for young researchers. Soon we should expect the emergence of new unexpected inventions, technologies, control systems. The task of railway science is not to lag behind and to systematically engage in solving a major problem of developing specific solutions for using fundamental achievements of the fourth industrial revolution for rail transport. At the same time, the use of the results of the completed study will make it possible to specify the directions of promising research in the field of technical and technological development of railways.

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